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Techno-ecological approach and Evidence-based Biophilic design for the implementation of Vertical Greenery Systems

Laboratory experimentation and Socio-ecological exploration in urban contexts

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Politecnica di Torino

Techno-ecological approach and Evidence-based Biophilic design for the implementation of Vertical Greenery Systems

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Matilde Molari
2023

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Abstract

The increasing urbanization of densely populated areas poses environmental and social challenges that require sustainable and *nature-inspired* solutions. Green walls, as a crucial component of urban green infrastructure, are gaining momentum in enhancing urban sustainability and reintroducing nature into cities. This doctoral thesis tackles the dual challenge of an holistic urban sustainability through *data-driven* and *evidence-based* design for innovative vertical greenery systems.

The first work discussed in the present thesis develops a laboratory experiment evaluating six alternative growing media from local bioresources for the implemementation of a circular strategy in the territory. Findings underline the suitability of lignin-rich materials as effective growing media amendments for the tested plant species, providing crucial insights for the utilization of local lignin-rich bioresources in various geographical contexts. Through a multi-criteria matrix baseline as guiding tool, a design-by-components strategy is introduced as sustainable vertical greenery systems aproach for reducing life cycle impacts.

The second work investigates the social impacts of vertical greenery systems, employing a socio-ecological perspective to assess green walls Restorative capacity. Naturalistic observation and a survey reserach reveal high Perceived Restorative capacity of two real case study living walls, showing their ability to attract people and influence urban space use. This research addresses a literature gap on social benefits, contributing to *evidence-based* biophilic design and guiding urban policy for resilient, biophilic cities.

Collectively, these two interrelated studies contribute to introducing a *data-driven* and *evidence-based* biophilic design of vertical greenery systems in order to effectively guiding policy-making processes in urban planning and fostering the creation of resilient and biophilic cities. Furthermore, the examination of environmental and social concerns of green walls fosters the definition of a holistic dimension to the sustainability assessment of these structures in urban environments.

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Introduction

Over the past five decades, the phenomenon of rapid urbanization has significantly transformed the contemporary urban landscape, resulting in a discernible reduction in urban green spaces and the fragmentation of vegetation extending beyond city limits (Medl et al., 2017). This urban expansion, characterized by the unbridled proliferation of impermeable surfaces such as concrete and asphalt, has given rise to adverse consequences, including compromised natural ventilation and soil permeability (Susorova et al., 2013; Koch et al., 2020). The accelerated pace of urbanization has introduced consequential environmental and social challenges, posing threats to human well-being and the overall sustainability of urban ecosystems.

These deleterious impacts on the urban environment manifest prominently in the form of heightened temperatures, commonly identified as the urban heat island effect. The dearth of extensive vegetation exacerbates challenges related to the abatement of pollutants generated by vehicular traffic, a prevalent issue in densely populated modern cities (Pettit et al., 2020). Over the past three decades, scholarly and planning efforts have sought solutions, exploring urban reforestation and nature-inspired approaches as viable means to address these pressing issues (Dorst et al., 2019). The focus of urban design has undergone a transformative shift towards the integration of natural processes, fostering urban regeneration through the infusion of novel social and environmental functions into the urban fabric (Perrone and Russo, 2019).

In this context, green walls or vertical greenery systems have emerged as pivotal elements influencing the design, construction, and rejuvenation of urban spaces. Representing a departure from conventional approaches, vertical greenery systems offer a flexible and non-invasive solution to the spatial constraints at ground level, concurrently redefining the utilization and aesthetics of the urban grid (Manso & Castro-Gomes, 2015).

The adoption and application of vertical greenery systems can be traced back to ancient civilizations, experiencing a noteworthy evolution in recent years, propelled by multidisciplinary research endeavors. Presently, a heightened awareness of the intricate environmental challenges confronting urban areas has prompted innovative investigations into vertical greenery systems, charting new territories of research and development. This evolving landscape indicates a promising trajectory for the continued enhancement and refinement of vertical greenery systems, providing sustainable solutions to the complex challenges posed by contemporary urbanization.

This doctoral thesis is devided into five chapters. The thesis is mainly divided into two work of reserach. Both are based on exeperimental reserach but declined and oriented towards different - and tematically opposite - directions.
In the first chapter the scenario and tehoretical backgorund in which the thesis topic is inserted are presented and discussed. This chpater is meant as a preliminary body of knowledge through to which interpret and understand the core and aim of the research.
In the second chapter the results of the preformed desk research at the beginning of the doctoral path are presented. In this chapter fundamental information that lead the direction of the thesis reserach are introduced as results of a mix method of review: one bibliometric literature review and a case studies analysis.
In the third chapter the first experimental reserach work is presented. In this work implying laboratory experiment the sustainability of growing media of vertical greenery systems is explored through local-bioreosurces experimentation. Through this work design practice is poposed in a *data-driven* approach as efficient method to improve the sustainability of vertical greenery systems design.
In the forth chapter the second experimental work is presented. Through this work a field inspection was developed to investigate vertical greenery systems influenceon people experience of urban space. This work proposes an an evidence-based approach to biophilic design. The aim of both experimental works is to develop and propose replicable

methodologies supporting and guiding a more reliable design process for vertical greenery systems
The final part of the thesis closes the work with reflections and conclusions on the results obtained and the implications of the methodology applied.

Chapter 1

Greening the city envelope
Scenario and technologies

Synthesis of the chapter

The following chapter serves as a preliminary introduction, elucidating the foundational knowledge essential for interpreting the aim, scope, and methodological trajectory followed in the research work of this doctoral thesis. Key concepts such as renaturation processes, urban greening, vertical greening, urban ecology, and the socio-ecological perspective are fundational concepts that define the borders and objectives of the work that will be presented.

Renaturation processes, denoting the restoration of natural features within urban landscapes, stand as a cornerstone concept. The integration of green spaces into urban environments, commonly known as urban greening, represents another fundamental element. Furthermore, the vertical greening concept, involving the incorporation of vegetation on vertical surfaces, adds a distinctive dimension to the discourse. Urban ecology provides a lens through which to understand the intricate interactions between urban environments and all the ecological systems within them. The socio-ecological perspective, on the other hand, broadens the scope by considering the reciprocal relationships between human societies and the ecosystems they inhabit.

As navigating through this academic exploration, these conceptual pillars will guide the understanding, facilitating a comprehensive overview of renaturation processes, urban greening, vertical greening, urban ecology, and the socio-ecological dynamics that underscore the research focus.

1.1 Renaturing cities

In the contemporary context defined by 21st-century imperatives, the call to rehabilitate and nurture urban vegetation resonates prominently among policymakers, urban planners and citizens. Going beyond aesthetic considerations, this imperative signifies a concerted endeavor to safeguard the vitality and well-being of urban ecosystems across current and subsequent generations (Pickett et al., 2016).

This call to action is closely tied the principles of urban ecology, city resilience, and ecological symbiosis which explore the complex interactions between human settlements and the environment around them (Horn & Proksch, 2022).
Urban ecology works as a lens to understand how vegetation, biodiversity, human activities and ecosystem services work in urban areas, giving valuable insights into the various relationships that

Figure 1.
The urban envelopes can be transformed by living nature (Houtouwan village, Johannes Eisele/AFP/Getty Images).

shape city life (Wanmo et al., 2020). In this context, the significance of bringing back urban vegetation becomes crucial, aligning with ideas of ecological resilience and sustainable city development (Figure 1).
This process of ecological transition of cities is closely linked to the concept of city resilience and climate change adaptation. Resilience in the urban setting is the ability of cities to adapt, withstand shocks and recover from disturbances, ensuring essential functions continue and the residents' well-being is secure (Olivieri, 2022)). Bringing back urban vegetation plays a pivotal role in boosting city resilience, contributing to the creation of more adaptable and responsive urban ecosystems (Francis & Lorimer, 2011).

From the resilience thinking, efforts for urban vegetation restoration enhance cities to adapt to environmental changes and challenges, ranging from extreme weather to health crises (Boulanger, 2023). These strategies, also applying collaborative initiatives and innovative approaches, resonate with the core ideas

of urban ecology, emphasizing how ecological, social and economic systems are interconnected in urban environments.

1.1.1 Towards a biophilic city

As global urbanization continues to surge, the biophilic city concept becomes increasingly relevant in its mission to reshape the cityscape into an ecosystem where urban and natural elements coexist synergistically. Introduced by Beatley (2008), the idea of the Biophilic city propose that urban environments have the potential to be significantly more infused with nature, offering wide opportunities for meaningful connections between city dwellers and the natural world. The biophilic city concept represents a visionary approach to urban planning and design that aims to harmonise the urban environment with the intrinsic human need for a deep connection to the natural world.

Coined by social psychologists Eric Fromm in 1964 and furtherly developed by biologist Edward O. Wilson in 1984 and Stephen Kellert in 1993, “Biophilia” is a scientific hypothesis refering to the innate human tendency to seek connections and afiliate with nature and life-like features of the non-human environemnt (Kellert & Wilson, 1993) (Figure 3).
Applied to the urban context, this concept recognizes the pressing need to create

environments that prioritize both human well-being and ecological vitality as interconnected aspects.

Biophilic cities are urban spaces that systematically integrate nature into their design, planning, and functioning. They feature green infrastructure, abundant public green spaces, urban forests, green roofs, vertical greening and an array of living elements that invite urban dwellers to interact with and immerse themselves in the living world (Figure 2). These cities prioritize the well-being of their citizens ultimately leading to improved quality of life, physical and mental health, reduced pollution and increased biodiversity.

Key principles of the biophilic city concept include:

Biodiversity and Habitat Preservation: Biophilic cities actively work to conserve and enhance urban biodiversity, creating and maintaining habitats for various species.

Urban Greening: Embracing green spaces, parks and urban forests, biophilic cities offer residents accessible areas for relaxation, recreation and contemplation. These green lungs mitigate the urban heat island effect, enhance air quality, and provide opportunities for urban agriculture.

Figure 2.
Vertical reforestation in Singapore.

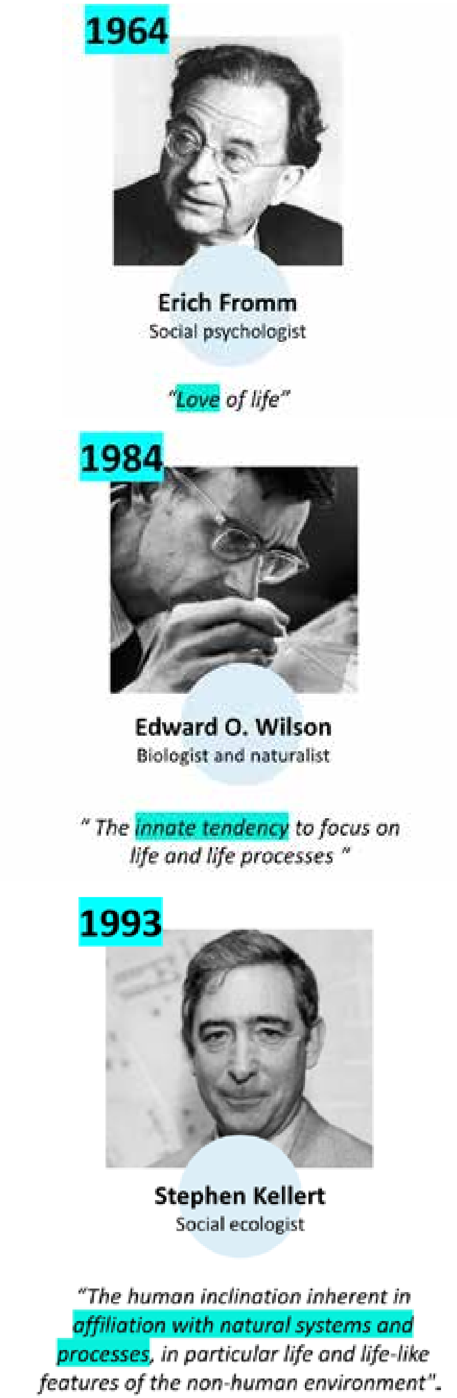


Figure 3. Biophilia Hypothesis. Concept evolution and main contributors.

Community Engagement: Communities are actively involved in the planning and decision-making processes, ensuring that urban development is rooted in local values and priorities.

Resilience to Climate Change: Biophilic cities are better equipped to handle the challenges of climate change, as their green infrastructure absorbs excess rainwater, reduces heat and sequesters carbon.

Cultural and Aesthetic Significance: Biophilic cities emphasize the beauty and cultural significance of the natural environment within the urban context, fostering an emotional connection to the recovered city natural elements.

1.1.2 The urban greening

In addressing the multifaceted challenges posed by urbanization, the integration of vegetation within urban environments, commonly referred to as urban greening, emerges as a comprehensive and sophisticated solution (Fig. 4). This approach, recognized for its efficacy, draws upon an amalgamation of scientific insights and practical applications to

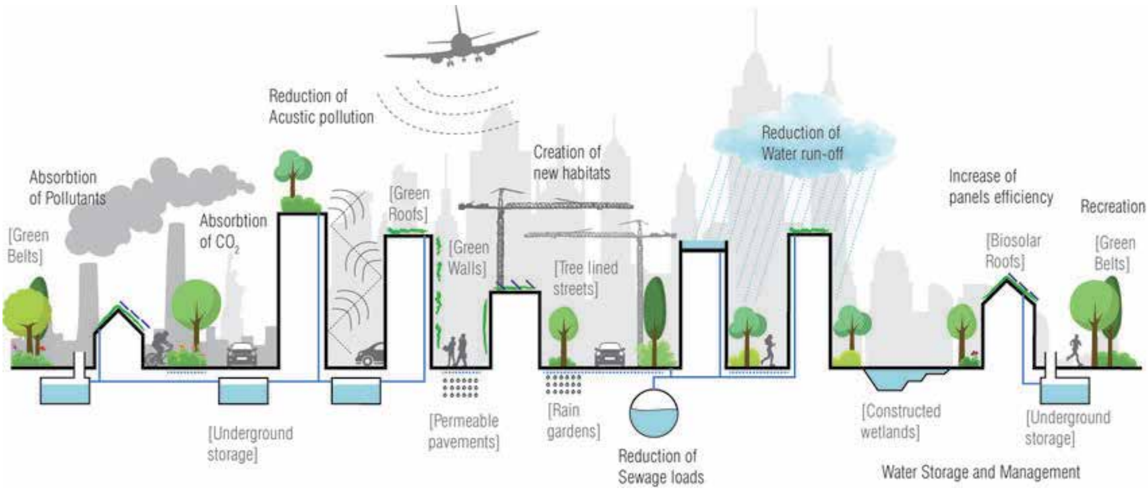


Figure 4. Urban ecosystem services offered by urban green infrastructure.

address diverse environmental and health concerns (Petzold & Mose, 2023). Vegetation in cities offers numerous ecosystem services that enhance an healthy funcioning of the city.

Urban areas grapple with elevated temperatures compared to their rural counterparts, attributable to the thermal absorption properties of built structures and paved surfaces (Santamouris, 2020). Urban greening strategies, encompassing tree planting and the creation of green spaces, play a pivotal role in mitigating the urban heat island effect. Through the provision of shade, induction of atmospheric cooling via evapotranspiration process urban greening enhances overall urban thermal comfort.

Urban regions often contend with atmospheric pollution, posing significant threats to human health (Bikis, 2023). Vegetation, particularly trees and plants, assumes a critical role in capturing and filtering airborne pollutants. Employing the process of phytoremediation, wherein plants absorb pollutants and release purified oxygen, urban greening significantly contributes to the amelioration of air quality and the enhancement of respiratory well-being.

The trajectory of urbanization invariably results in habitat loss and a decline in biodiversity (Li et al., 2022). Urban greening initiatives, involving the introduction of green spaces and native flora, act as sanctuaries for diverse species, including crucial pollinators (PMcDonald et al., 2020).

Impermeable surfaces inherent to urban landscapes intensify stormwater runoff, leading to potential flooding and the conveyance of pollutants into aquatic bodies (Lapointe et al., 2022). Urban greening strategies, exemplified by the implementation of green roofs and permeable pavements, serve to mitigate stormwater-related challenges by absorbing and decelerating runoff. This, in turn, reduces flooding risks and improves water quality.

Access to green spaces is positively correlated with improved mental health outcomes (Syamili et al., 2023). Natural environments act as recovery space from the stresses inherent in urban living, facilitating psychological restoration. Furthermore, the provision of opportunities for physical activity within green spaces tangibly contributes to overall health enhancement and the promotion of an active lifestyle.

Moreover, vegetation serves as a natural sound barrier, mitigating urban noise and fostering a more calm urban environment (de Oliveira et al., 2022). This aspect is particularly pertinent in densely populated areas where noise pollution is a contributing factor to heightened stress levels and associated health issues.

Green spaces and vegetation significantly

Figure 5. Vertical greenery systems applied to a building facade

enhance the visual appeal of urban landscapes, creating aesthetically pleasing and inviting environments for residents, workers, and visitors (Simpson et al., 2023). Public parks, community gardens, and tree-lined streets play a crucial role in fostering a sense of community identity and social cohesion among urban residents.

1.2 Vertical greenery systems

In response to the pervasive issue of the urban green deficit – the marked absence of natural vegetation within city boundaries – and the densification of urban grid, vertical greenery systems are an ever encrese promising solution for flexible interventions (Fig. 5). The utilization of vertical greenery systems stands as a strategic approach to rehabilitate underutilized urban spaces. Vertical greenery systems make efficient use of free vertical envelopes on buildings and urban infrastructures, transforming once neglected spaces into vibrant and environmentally beneficial installations.
In the current era, there is a growing awareness of the imperative for urban regeneration and sustainable development (European Commission, 2020). Governments and city planners are increasingly implementing programs and initiatives aimed at transforming cities into more sustainable, resilient and healthy spaces. The integration of outdoor vertical greenery systems aligns seamlessly with

Figure 6. Direct green facades.
Climbing plants growing directly on the wall.

Figure 7. Indirect green facade.
Climbing plants growing on trellis.

these goals, representing a tangible and multifunctional solution that addresses both environmental and social challenges. As a result, interdisciplinary research in this field continues to thrive, contributing to the ongoing evolution of urban landscapes towards greater sustainability and livability.

1.2.1 System description

Vertical greenery systems are transforming urban landscapes by addressing the multi-faceted challenges posed by the scarcity of greenery in cities (Bustami et al., 2018). By incorporating green walls into urban design, cities can optimize the use of available space in a creative alternative manner.

Vertical greenery systems are a subset

Figure 8. Continuous living walls system.
Compact coverage of different plant species.

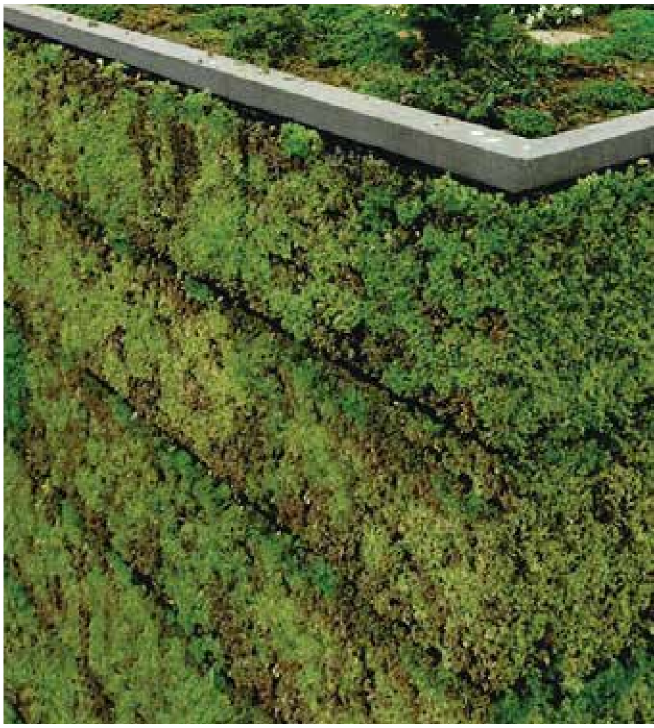


Figure 9. Modular living wall system.
Vegetated modules composing the living wall.

of nature-based solutions, encompassing technologies and applications that leverage or restore natural elements to reactivate stressed, weakened, or interrupted ecosystem services within cities (Connop et al., 2016). Within the diverse range of nature-based technologies, including high-tech solutions and substantial infrastructural interventions, vertical greenery systems are space-efficient green infrastructure that support the growth of plants on vertical surfaces. For this reason vertical greenery systems respond to the problems of the contemporary city in a flexible and non-invasive way, obviating the scarcity of space at ground level and reinterpreting the use and image of the urban grid.

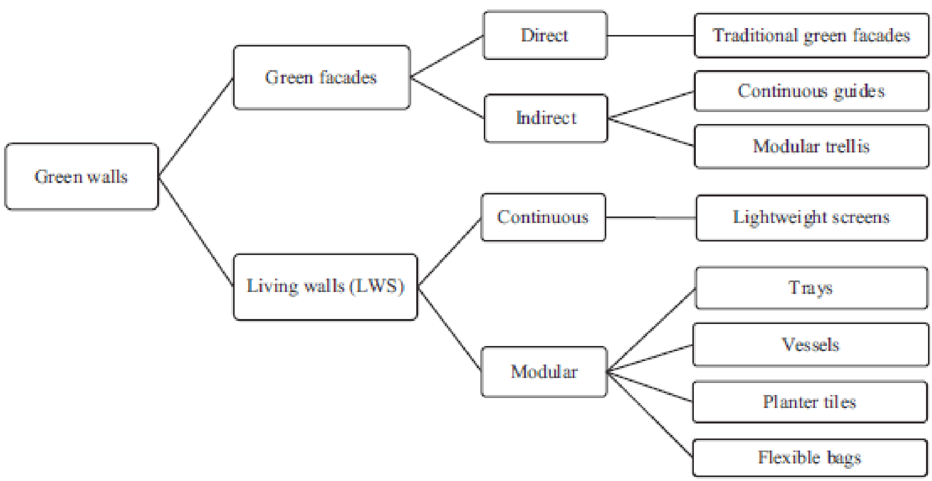
According to their structure, components and materials vertical greenery systems can be mainly categorised in green façades and living wall systems (Figure 10) (Manso and Castro-Gomes, 2015).

Green façades are the anciest solution of vertical greenery system and consist in the use of climbing or hanging plants growing directly on a wall or indirectly on a support

system (Vox et al., 2018).
Direct green facades (Figure 6) involve plants attaching directly to the wall. Direct green facades can grow spontaneously and are characterised by the growth of plants directly on a vertical surface, basing their structure on the adhesion capacity of climbing plants or natural covering of hanging plants.
To facilitate and easily manage vertical growth, indirect green facades (Figure 7) require support structures. These may include trellises, cable systems, or specialized frameworks attached to the buildin façade, they are generally formed in steel (Ottelè et al., 2011). These structures provide a framework for the plants to climb and develop, creating a green tapestry. Indirect green facades can be categorised into continuous or modular typlogies.
Continuous indirect green facades employ a singular support structure to direct plant development across a surface.
Modular indirect green facades are composed of multiple modular elements installed along the surface. In such cases, plants may root in the ground or in planters, guided to grow along the support structure.

Living wall systems are a more recent technology than green facades. They consist of a supporting structure attached to the wall that contains growing medium and vegetation. Living wall systems

Figure 10. Vertical greenery systems typologies. Nomenclature and typologies of vertical greenery systems according to Manso and Castro-Gomez (2015).



are usually classified into modular or continuous systems (Perini et al., 2013).
The continuous systems (Figure 8) are generally characterised by a layer of lightweight and permeable screens, often geotextile, to support the plants roots growth.
The modular systems (Figure 9) is generally composed by modules incorporating growing medium to be hook to the anchoring systems attached to the vertical surface. For the installation phase, the modular system allow to growth in nursery the plants before the system installation. Modular living wall systems exhibit distinctions in composition, weight, and assembly and can take the form of trays, vessels, planter tiles or flexible bags. Living walls are more complex systems than green facades and provide a more uniform vegetation coverage, but they usually require frequent maintenance (Gunawardena and Steemers, 2019a, 2019b).

1.2.2

Figure 11. Vertical greenery benefits. Keywords and papers related to the environmental benefit of vertical greenery systems.

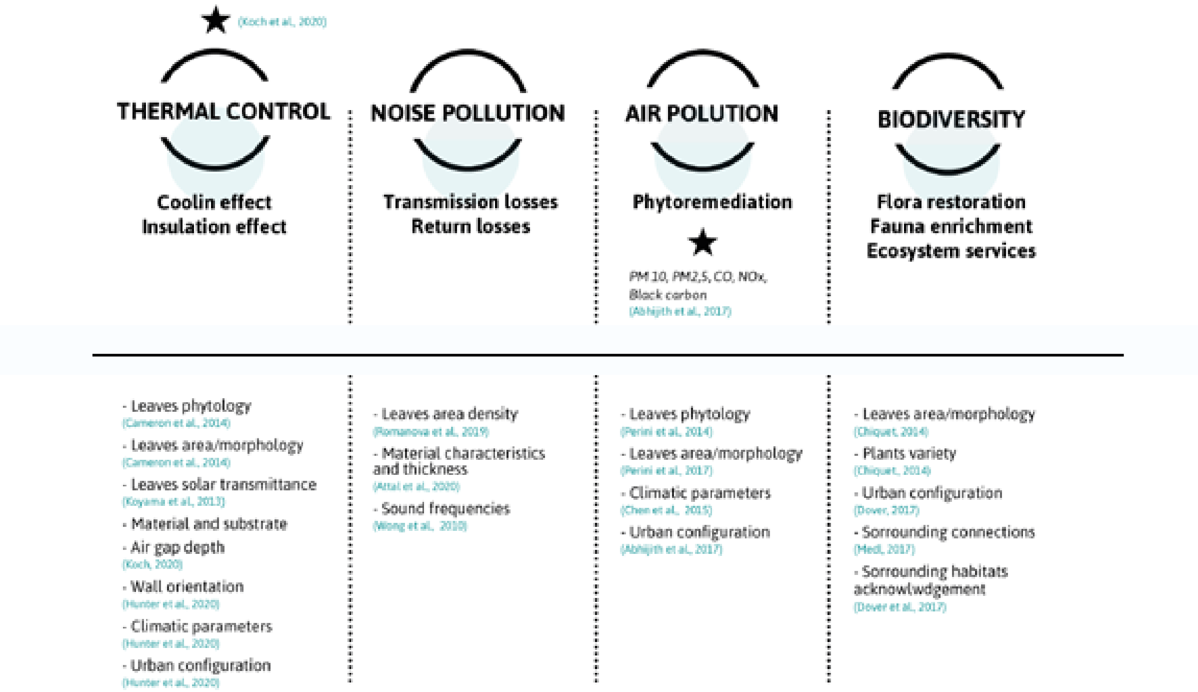


Figure 12. Multifunctional benefits. Vertical greenery systems offers diverse benefits through the multi-functions of their living and artificial components.

Vertical greenery systems benefits

Contemporary academic research increasingly proved the environmental benefits offered by vertical greenery systems. Programs and guidelines encouraging the use of vertical greenery systems in cities have become widespread. Initiatives like the New European Bauhaus and New Horizons 2020 promote the application of green walls as substantial contributions to build sustainable and resilient cities (European Commission, 2020).

Consequently, vertical greenery systems are integral to strategies for the green transformation of modern cities. In fact, vertical greenery systems yield multiple environmental and social benefits within the urban environment (Goel et al., 2022).

Below, the urban benefits offered by vertical greenery systems are presented.

For the understanding of green walls established opportunities and benefits in the urban environment accordigng to academic knowledge, a preliminary exploratory literature review on thirty scientific articles was carried out (Fig. 11).

Air pollution mitigation
Research studies (Srbinovska et al., 2021; Pettit et al., 2019) highlight the significant contribution of vertical greenery systems to the enhancement of air quality, as the vegetation within these systems actively absorbs pollutants and releases oxygen, creating a healthier urban atmosphere. This not only positively impacts the respiratory health of residents but also contributes to the overall ecological balance of the city.

Urban Biodiversity
In addition to improving air quality, vertical greenery systems play a crucial role in promoting urban biodiversity (Madre et al., 2015). By providing vertical habitats for various plant species, these green systems contribute to the creation of ecological niches within urban landscapes. This biodiversity enhancement is essential for maintaining a resilient and balanced urban ecosystem, fostering a harmonious coexistence between nature and the built environment.

Noise pollution reduction
Noise pollution reduction is another noteworthy benefit associated with outdoor vertical greenery systems. Studies (Susca et al., 2022) indicate that the vegetation in these systems acts as a natural sound barrier, absorbing and diffusing urban noise. This not only creates a more calm urban environment but also addresses the adverse effects of noise pollution on human health, contributing to a higher quality of life for city dwellers.

Urban microclimate control
The mitigation of the urban heat island effect stands as a significant ecological contribution of outdoor vertical greenery systems (Susca et al., 2022). The vertical greenery serves as a natural insulator, reducing the absorption of solar radiation by building surfaces and, consequently, lowering surface temperatures. This not only enhances the thermal comfort of urban spaces but also contributes to energy efficiency by reducing the demand for cooling in buildings.

Besides these environmental benefits that can be categorised in provisioning and regulatory ecosystem services, social benefits are also a relevant contribution coming from vertical greenery systems in the urban environment. These benefits rely in the complex sector of cultural ecosystem services and can be described as follows.

Well-being
The positive impact of outdoor vertical greenery extends to human well-being (Chung et al., 2022). The presence and aesthetic of vegetation has been linked to various psychological and physiological health benefits. The presence of vertical greenery systems, provides residents with opportunities for relaxation and stress reduction with consequently improved mental well-being (Faisal et al., 2018). This aspect, enclosed in the cultural ecosystem services, recognises the interconnectedness of environmental and social factors in shaping the overall urban

experience.

Aesthetics improvement
Aesthetic benefits are equally significant, as green walls maximize the utility of vertical space, a resource that often goes untapped in densely populated urban areas. By adorning building exteriors, green walls seamlessly merge with urban architecture, introducing an organic and refreshing element to the cityscape. This unique integration with structures provides cities with the opportunity to create distinctive visual identities, reinforcing the sense of connection of people with natural elements and processes .

Green walls represent a remarkable response to the urban green deficit, offering a holistic approach that addresses diverse challenges posed by urbanization (Figure 12). By offering holistic urban ecosystem services, green walls exemplify how innovative strategies can transform cities into more livable, resilient, and nature-integrated environments. .

1.3. Urban ecology and the "City as a Laboratory" Concept

Belonging to the biohilic city perspective, the "city as a laboratory" concept is an approach that views urban environments as unique dynamic experimental spaces for innovation, adaptation, and learning.
According to Urban ecology, cities are conceived as complex systems teeming with diverse populations and relations with the context, the intricate infrastructure and social systems that provide a unique setting for testing and refining solutions to a wide array of societal and environmental challenges.
In this concept, cities actively engage in experiments, pilot projects, and collaborative initiatives aimed at addressing a multitude of issues such as sustainability, transportation, housing, energy efficiency, and social equity (Figure 13). The goal is to gather data, analyze outcomes, and apply lessons learned to inform future projects, applications, urban policies and practices. It is an approach that acknowledges the need for adaptive, context-specific solutions in the ever-evolving current urban landscape. According to this perspective, cities become dynamic testing grounds where urban ecology principles are actively explored and incorporated into the development of biophilic environments.
Below keypoint structuring this perspective are presented.

Ecosystem Services Integration: Urban ecology, as a scientific framework, allows cities to analyze the services provided by their ecosystems and strategize on how to enhance them.

Monitoring and Assessment: Urban ecology principles lend to the creation of comprehensive monitoring systems that collect data on urban ecosystems. This information can be used in the "city as laboratory" approach to assess the

Figure 13. ProGIreg in Turin. Pilot poject on urban renaturation and community engagement with green infrastructure developed by the Living Lab of Mirafiori Sud district in Turin, Italy.

effectiveness of biophilic interventions and ensure that urban environments remain healthy and resilient.

Ecological Design: Urban ecology principles inform the design of biophilic cities by considering the specific ecological needs of the context or territory. Urban planners and designers can use this information to create urban environments that mimic natural ecosystems, enhancing their beauty and functionality.

Adaptive Governance: Urban ecology and the "city as laboratory" concept encourage adaptive governance, which is responsive to the changing needs of the city and the evolving understanding of urban ecosystems. As biophilic interventions are implemented, continuous assessment and adaptation can ensure that they meet their intended goals.

By combining urban ecology and the biophilic city concept within the framework of the "city as laboratory," cities

can evolve into living laboratories where observe, analyse and study processes and interconnected relations between natural and artificial elements inside them.
Adopting this perspective, biophilic cities are dynamic ecosystems where innovative experimentation continuously molds the urban fabric and where the coexistence of humans and the natural environment is mutually beneficial.

1.3.1 Data-driven and Evidence-based biophilic design

In this comprehensive vision of urban transformation, the crucial role of a data-driven and evidence-based biophilic design emerges as pivotal for achieving meaningful innovation in the sustainable development of biophilic cities (Beatley, 2011; Kellert, Heerwagen, & Mador, 2008).
Biophilic design incorporate natural elements, processes and reminiscences into the built environment, therefore it aims to create spaces that enhance the human-nature connection, promoting well-being, productivity and a sense of pleasantness.
Key principles of biophilic design include:

Integration of nature: Incorporating natural elements such as plants, water features, natural light and views of the outdoors into the design of buildings and interiors.

Natural shapes and forms: Using organic shapes, patterns and materials in the design, mimicking the structures found in nature.

Biomorphic forms and patterns: Incorporating designs that evoke natural patterns, such as the fractal geometry found in leaves or the branching structures of trees.

Natural light and ventilation: Maximizing the use of natural light and ventilation to create a healthier and more comfortable indoor environment.

Sensory stimuli: Engaging multiple senses by integrating sounds, textures, and scents associated with nature.

Prospect and refuge: Designing spaces that offer both open views (prospect) and enclosed, sheltered spaces (refuge), providing a sense of safety and connection with the surroundings.

Cultural and ecological connection: Reflecting the local ecology and cultural context in the design to create a sense of place and identity.

Holistic design: Considering the overall well-being of occupants by creating environments that support physical, mental, and emotional health.

Evidence-based biophilic design begins by recognizing that human connection with nature it’s deeply rooted in our biology and psychology (Wilson, 1984) and that this connection has quantifiable benefits

2 Dimensions, 6 Elements, and 72 Attributes of Biophilic Design (Kellert, 2008b)					
I. Organic or Naturalistic				**II. Place-based or Vernacular**	
1. Environmental features	**2. Natural shapes and forms**	**3. Natural patterns and processes**	**4. Light and space**	**5. Place-based relationships**	**6. Evolved human-nature relationships**
• Color • Water • Air • Sunlight • Plants • Animals • Natural materials • Views and vistas • Façade greening • Geology and landscape • Habitats and ecosystems • Fire	• Botanical motifs • Tree and columnar supports • Animal (mainly vertebrate) motifs • Shells and spirals • Egg, oval, and tubular forms • Arches, vaults, domes • Shapes resisting straight lines and right angles • Simulation of natural features • Biomorphy • Geomorphology • Biomimicry	• Sensory variability • Information richness • Age, change, and the patina of time • Growth and efflorescence • Central focal point • Patterned wholes • Bounded spaces • Transitional spaces • Linked series and chains • Integration of parts to wholes • Complementary contrasts • Dynamic balance and tension • Fractals • Hierarchically organized ratios and scales	• Natural light • Filtered and diffused light • Light and shadow • Reflected light • Light pools • Warm light • Light as shape and form • Spaciousness • Spatial variability • Space as shape and form • Spatial harmony • Inside-outside spaces	• Geographic connection to place • Historic connection to place • Ecological connection to place • Cultural connection to place • Indigenous materials • Landscape orientation • Landscape features that define building form • Landscape ecology • Integration of culture and ecology • Spirit of place • Avoiding placelessness	• Prospect and refuge • Order and complexity • Curiosity and enticement • Change and metamorphosis • Security and protection • Mastery and control • Affection and attachment • Attraction and beauty • Exploration and discovery • Information and cognition • Fear and awe • Reverence and spirituality

3 Experiences and 25 Attributes of Biophilic Design (Kellert, 2018)		
1. Direct Experience of Nature	**2. Indirect Experience of Nature**	**3. Experience of Space and Place**
• Light • Air • Water • Plants • Animals • Landscapes • Weather • Views • Fire	• Images • Materials • Texture • Color • Shapes and forms • Information richness • Change, age and the patina of time • Natural geometries • Simulated natural light and air • Biomimicry	• Prospect and refuge • Organized complexity • Mobility • Transitional spaces • Place • Integrating parts to create wholes

3 Categories and 15 Patterns of Biophilic Design (Browning and Ryan, 2020)		
1. Nature in the Space	**2. Natural Analogues**	**3. Nature of the Space**
• Visual Connection with Nature • Non-Visual Connection with Nature • Non-Rhythmic Sensory Stimuli • Thermal & Airflow Variability • Presence of Water • Dynamic & Diffuse Light • Connection with Natural Systems	• Biomorphic Forms & Patterns • Material Connection with Nature • Complexity & Order	• Prospect • Refuge • Mystery • Risk/Peril • Awe

Figure 14. Biophilic design frameworks . Combination of three frameworks of biophilic design, from Zhong et al. (2022) (adapted from Browning and Ryan, 2020; Kellert, 2018, 2008).

for human well-being, from reduced stress and improved mental health to enhanced physical health and overall quality of life (Ulrich, 2023) (Figure 14).

Conceived in the urban environment, the practice of evidence-based biophilic design demands rigorous research and *ad hoc* methods to understand the specific needs and preferences of citizens (Beatley, 2016). The derived data-driven insights on how individuals interact with nature within the city context - whether through visual contact with greenery, the presence of water features or opportunities for physical engagement with the natural world (Beatley, 2011) - can guide the selection of design elements, material choices, and architectural features aligning with human needs and desires.

Furthermore, evidence-based biophilic design underscores the importance of measurable outcomes (Kellert, 2012). It emphasizes the systematic collection of data to evaluate the impact of biophilic interventions within the urban landscape.

This scientific approach is invaluable for not only validating the efficacy of biophilic design but also for continually refining and optimizing urban spaces. When data is collected, analyzed, and used to make informed decisions, urban planners and designers can adapt to evolving needs and preferences.

Moreover, evidence-based approach allows cities to make a compelling case for investing in biophilic elements by investigating the complexity of intangible benefits they bring to the well-being and health of their residents.

In this framework, evidence-based biophilic design aligns with the “city as laboratory” concept (Byrne, 2022). Cities that actively embrace this approach become dynamic testing grounds for innovative solutions. The data collected from these experiments contributes to a growing body of knowledge that informs future urban projects. The interplay between urban ecology and biophilic design is further strengthened, as ecological insights are translated into actionable design strategies based on real-world outcomes.

Data-driven and evidence-based biophilic design provides the critical link between urban ecology, the biophilic city concept and the “city as laboratory” concept. The use of data to inform design ensures that the integration of nature into the urban environment is not a mere aesthetic choice but a strategic one that enhances ecological resilience and human well-being.

This approach underscores that creating biophilic cities is not a one-time endeavor but an ongoing journey (Wu et al., 2014). As urban environments continue to evolve, the need for dynamic, data-informed design becomes increasingly essential. Develop data-driven and evidence-based biophilic design into the fabric of cities, pave the way for sustainable, resilient, and harmonious urban settings. (Browning et al., 2016).

Chapter 2

Vertical greenery systems
State-of-the-art and case studies

Synthesis of the chapter

The following chapter provides an in-depth exploration of the desk research developed since the beginning of the doctoral program. To obtain a comprehensive understanding of the subject matter concerning vertical greenery systems and their functions and benefits within urban contexts, a mixed methodologically approach was adopted, combining both a bibliometric literature review and a case study analysis. The bibliometric literature review was instrumental in surveying and synthesizing the existing body of scholarly work related to vertical greenery systems. This approach enabled the extraction of valuable insights into the functions, innovations, and applications of these systems as documented in academic research. Concurrently, a case study analysis was conducted, delving into real-world implementations of vertical greenery systems. This investigative process aimed to provide a nuanced perspective on the practical applications and outcomes of such systems in diverse urban settings. By integrating these two analytical methods, a reliable and comprehensive background knowledge base was established. This foundational understanding encompasses the multifaceted dimensions of vertical greenery systems, ranging from their functional aspects to innovative features, and extends to their real-world applications in both research and practical urban implementations.

The chapter exposes the author's reserach partly presented in Comino et al. (2021), published in AGATHÒN | International Journal of Architecture, Art and Design.

2.1 Exploring the current scenario

Over the last fifty years, the process of urbanisation has characterised and modified the morphology of contemporary cities at an increasingly accelerated rate. This process has led to a continuous decrease in green spaces within the urban grid and to the segmentation of vegetated covers outside it (Medl et al., 2017). This process of continuous expansion has led to an uncontrolled increase in concrete and asphalt surfaces, reducing natural ventilation and soil permeability (Susorova et al.. 2013; Koch et al., 2020). The main negative effects on the urban environment translate into ever-rising temperatures, the so-called urban heat island effect. Moreover, the absence of widespread vegetation does not allow the mitigation of pollutants produced by vehicular traffic, which globally characterises contemporary congested cities (Pettit et al., 2020).
In the last thirty years urban planning and academic research have explored and implemented urban re-forestation solutions as a response to this critical situation. The design of public spaces and infrastructures focuses particularly on the integration between natural processes and the urban environment, promoting an urban regeneration based on the activation of new social and environmental functions in the city (Perrone and Russo, 2019).
Starting from the innovative aesthetic

Figure 15. Prefectural International Hall. *Green over the gray* application by Emilio Ambasz, Fukuoka, Japan, 1990.

Figure 16. Caixa Forum, Madrid. Application of *Le Mur Végétal* system by Patric Blanc in 2001.

research of visionary projects such as the concepts of Brazilian architect Lina Bo Bardi in the early 50s, and the realisation of the SITE group during the '70s (Figure 16), the idea of "re-naturalising" (Yudina, 2019) the urban environment through the application of vegetation on city buildings spread through the world.

The application of vertical greenery systems is the result of constantly increasing research on this topic. Since the 1990s, thanks to Patrick Blanc's groundbreaking research and his well-known *Mur Végétal*, vertical greenery systems have seen a rise in the popularity. Within the urban environment, the validity of these solutions lies in the increasing availability and size of vertical surfaces of buildings and infrastructures in the urban grid (Loch et al., 2008). This is a crucial aspect considering the current rate of increasing urbanisation. Hence,

green walls can contribute to achieving sustainable urban greening in a context of lack of free space in the contemporary urban fabric. Moreover, these solutions can contribute to developing alternative greening strategies and are considered an innovation in the fields of ecology, horticulture and buildings (Virtudes, 2016).
In the past they were applied mainly in image retrofitting interventions on landmark building, due to their strong aesthetic value. The CaixaForum in Madrid (Figure 16) and the Citi Data Center in Frankfurt (Manso et al., 2016) are two famous examples of the aesthetic use of outdoor vertical greenery systems.

Today academic research focuses increasinlgy on the environmental benefits offered by this typology of green infrastructure, in connection with a growing attention to safeguarding city livability. Programmes and guidelines encouraging the use of vertical greenery systems in cities are widely diffused today. The New European Bauhaus and the New Horizons 2020 are two of the main programmes that sustain the application of green walls as real contributions for the assessment of sustainable resilient cities (European Commission, 2020). Hence, VGS are solutions included in the strategies for the green transition of contemporary cities.
These technologies exploit the vegetation component to mitigate some criticalities of the urban environment. In fact, thanks to the presence of vegetation and their phytological process, vertical greenery systems can mitigate the concentration of gaseous pollutants, noise pollution, the urban heat island effect additionally supporting urban biodiversity and the psychophysical well-being of citizens (Dover, 2015; Susorova et al., 2014; Weerakkody et al., 2018). The 11 SDG of the Agenda for Sustainable Development for 2030 promotes making "cities and human settlements inclusive, safe, resilient and sustainable" (United Nations, 2015). Following this purpose, outdoor vertical greenery systems can be utilised as a key strategy for improving the cleaning of air and water, for mitigating high temperatures and for promoting local biodiversity and the well-being of citizens. As multifunctional solutions, capable of responding to environmental and social issues, outdoor vertical greenery systems fit into a highly interdisciplinary field of research.
At present, awareness about the need for urban regeneration is dramatically increasing as observed by the implementation of programmes and initiatives aiming at making cities more sustainable and healthy (European Commission, 2020). Outdoor vertical greenery systems appears to be a promising solution to redefine urban contexts but still remains under-researched. Current urban programmes and initiatives are creating a growing demand to foster and diffuse nature-based solutions technologies as solutions to achieve city resilience. However, the assessment of impacts and benefits of specific nature-based solutions typologies is necessary in order to ease and support the decision-making process

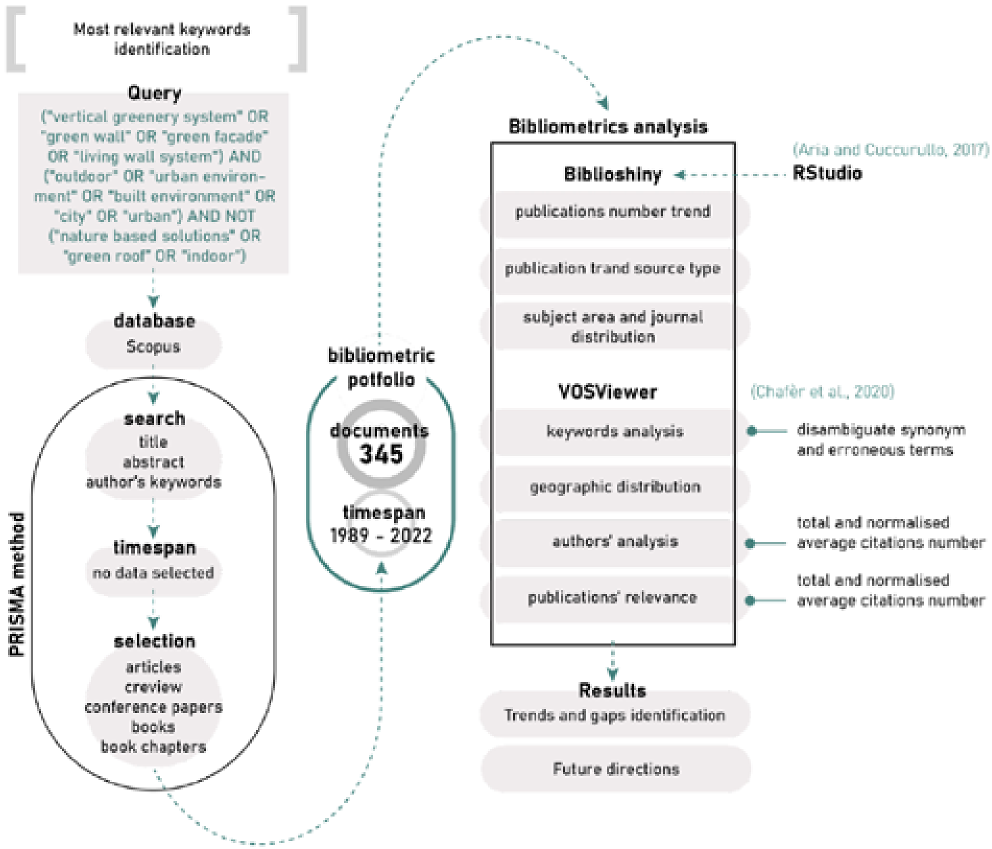


Figure 17. Research structure. Process and main reference followed for the literature review.

in urban planning. Furthermore, the multi-purpose nature of this type of technology and the evolution in issues and research fields regarding urban ecology has resulted in a flourishing academic literature which is yet to be systematised. Therefore, the aim of this chapter is to offer an overview on the state of the art of reserach and applications of outdoor vertical greenery systems. It will present a bibliometric literature review and real case studies analysis in order to identify trends, gaps and the main topics regarding vertical greenery applied to the contemporary urban environment.

2.2 Bibliometric literature review

A bibliometric review has been used to document the complexity of topics and information (Verrall and Pickering, 2020) in the research field of outdoor vertical greenery systems (Figure 17).
Bibliometric methods help to map the science and are very useful in the case of research synthesis, especially for the systematic ones. This methodology permits the analysis of a great number of documents and to obtain clear information about trends, areas of research and existing relationships between researchers and countries worldwide (Pritchard, 1969). Although bibliometrics is mainly known for quantifying scientific production and measuring its quality and impact, it is also useful for displaying and analysing the intellectual, conceptual and social structures of research. Network structure is often used to model the interaction among authors, papers/documents/articles, references, keywords, etc. Thus, in order to have a picture of the global state of the art of outdoor vertical greenery systems different bibliometric tools were used.

Section 2.2 offers not only a deep understanding of the outdoor vertical greenery systems state of the art but also highlights future directions in order to identify opportunities in academic research. Referring to the work of Chafèr et al., 2020, systematic literature reserach on this topic can be a useful body of information to support the decision making process in real urban regeneration projects.

2.2.1 Methodology of the literature review

Bibliometrics is defined as “the application of mathematical and statistical methods to books and other media of communication” (Pritchard, 1969). According to several authors bibliometric analysis can be applied as a review method to extrapolate the evolution and state of the art of a particular research field and, moreover, to interpret possible future development of it (Sanchez et al., 2017; Muhuri et al, 2019).
In order to manage the different information extrapolated from each document, the software Excel, Biblioshiny and VOSviewer were used (Jan van Eck and Waltman, 2020). Those tools allow to obtain and to visualise the metadata contained within the selected documents, analysing the relations within different data categories, i.e. authors, keywords, sources, countries, etc.. Scopus database has been selected for this study since it is one of the largest databases of peer-reviewed documents offering a very broad overview of the world’s research output in the vertical greenery research field (Echchakoui, 2020).
As a first step in the methodology, it was carried out an analysis of the amount of publications in Scopus, using different queries strings until reaching the correct

and most explanatory one to carry out the study. Considering the ambiguity that still characterised the nomenclature of vertical greenery systems, the first row of the query contains the most frequent terms that identify the system typology (Manso et al., 2015). To set the literature research, no start date was specified in Scopus site, allowing to identify the earliest papers in the literature.

To identify the bibliometric portfolio, the PRISMA method has been used. This is the most used reporting item for systematic review and meta-analysis flow diagram, it was introduced by Moher et al. 2009 and is often used to conduct bibliometric analysis. The PRISMA method is an iter composed of four steps to identify a dataset for analysis: (1) identification of studies, (2) screening, (3) eligibility, and (4) inclusion.

Identification of studies - To delimit the research to the outdoor urban context applications, keywords such as “outdoor”, “urban environment”, “city”, “urban” and “built environment” were added in the search query. Furthermore, in order to obtain an effective focus on the vertical greenery systems, “nature based solutions” keyword was excluded to eliminate documents that do not focus exclusively on vertical greenery systems.
After a preliminary screening of the main contributions on the theme of outdoor vertical greenery systems, it was decided to exclude also the “green roofs” keyword, since research on urban greenery often relates vertical greenery systems and green roofs. Moreover, the keyword “indoor” has been excluded, ensuring this way that all the literature concerning the huge topic of indoor green walls will not be included in the bibliometric portfolio. Finally, the following search pattern was applied considering the occurrence of the selected keywords within documents’ titles, abstracts and keywords to obtain the larger literature available on the interested topic (Ravikumar et al., 2015):

TITLE-ABS-KEY (“vertical greenery system” **OR** “green wall” **OR** “green facade” **OR** “living wall system”) **AND** (“outdoor” **OR** “urban environment” **OR** “built environment” **OR** “city” **OR** “urban”) **AND NOT** (“nature based solutions” **OR** “green roof” **OR** “indoor”)

Screening - To conduct the screening step, the search has been set up considering article paper, review paper, book, book chapter and conference paper typology. In this way unclear or less relevant contribution typologies have been excluded.

Eligibility - After the elimination of duplicates, titles and abstracts have been red. Titles and abstracts have been controlled to ensure the real pertinence to the only urban outdoor context. In the affirmative case contributions have been included in the bibliometrics portfolio.

Inclusion - Once the research was done in Scopus database, it was found that the first publication which appears in the literature was from 1989. Therefore, the bibliographic portfolio for this study, referring to the time frame from 1989 to 2022, includes 345 documents found in Scopus. This search was done in February 2022, and therefore, includes 12 documents for that year. Considering the high number of publications in relation to other years, it was decided to include them in the analysis, even if they are not totally representative for the whole current year.

Thus, the bibliographic portfolio was analysed using the software Biblioshiny and VOSViewer, to understand the correlation and evolution in time among bibliographic metadata, i.e. keywords, authors, titles, abstracts and affiliations of the documents, documents citations, topics and correlations between documents and authors. For major detail about the use of Biblioshiny we refer to Aria and Cucurullo (2018).

2.2.2 Bibliometric tools

Biblioshiny and VOSviewer were selected to analyse bibliographic metadata. This tool allows the development of bibliometric analysis presenting and manipulating data without the use of coding skills. This characteristic makes this type of analysis open and accessible to different backgrounds of research. This tool combines the functionality of the bibliometrix package of RStudio with the use of a web app in the Shiny environment. Bibliometrix is an open-source tool developed by Aria and Cuccurullo (2018) and programmed in an R environment for performing comprehensive science mapping analysis based on coding skills.
Biblioshiny was used to visualise and analyse the data from four aspects including annual production, sources, countries, and documents.

VOSviewer is a freely available software that collects the bibliographic data from bibliographic databases and datasets to build graphical maps, networks of scientific publications, scientific journals, researchers, research organisations, countries, keywords, or terms (van Eck and Waltman, 2010). The items in these networks can be connected by co-authorship, co-occurrence, citation, bibliographic coupling, or co-citation links. To construct a network, data from Web of Science, Scopus, PubMed, RIS, or Crossref JSON files can be used. Furthermore, this program allow to visualise and explore these maps providing three different visualisations: (1) the network visualisation, (2) the overlay visualisation and (3) the density visualisation, showing particular concentration. In the network visualisation the items of the map are represented by their label and by default also by a circle changing in size according to the weight of the item. In the overlay visualisation items are colored according to a coloured scale depending on items scores and the current selected parameter. In the density visualisation, items are represented by their label in a similar way as in the network visualisation and the overlay visualisation. Each point in the

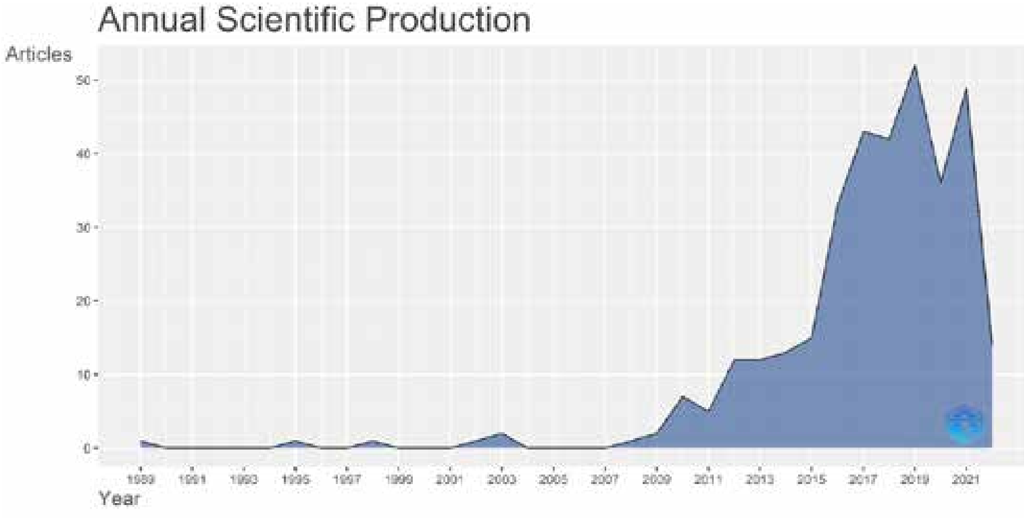


Figure 18. Publications trend. The identified bibliographi portfolio covers the period from 1989 to 2022.

item density visualisation has a colour that indicates the density of items at that point (van Eck and Waltman, 2018).

Biblioshiny and VOSViewer are similar in data analysis but with some differences. Both software based their information on three different level metrics: source, documents and authors. Nevertheless, the combined use of VOSViewer has been chosen in the present work to add a lens of analysis otherwise impossible to develop in the Biblioshiny tool. In fact, despite Biblioshiny functionalities, VOSViewer provides data networks showing temporal modification of the metadata analysed, e.g. keywords, authors, papers. This functionality can be activated using the item overlay visualisation selecting as score parameter the “average publication year”. This functionality is essential to develop a coherent interpretation of the state of the art, evolution and future development of an analysed topic.

2.2.3 Main information about the bibliometric portfolio

The collection obtained covers a timespan from 1989 to 2022 and contains 345 documents. The contributions derived from a total of 183 sources, i.e journals, books, conference. The bibliometric portfolio collects works developed by a total of 918 authors, in which 880 authors of multi-authored documents and 38 as authors of single-authored documents, just less than the 5% of authors. Single authored documents are about 11,30% of the total bibliometric portfolio, with 39 contributions. The medium number of authors per paper is about 2.66 and the collaboration index is 2.88. The average number of co-authors per document is 3,46. The average citation per document is about 20,46 and the average citation per year per document is 2.547.

2.2.4 Trends in the number of publications

As can be seen from Figure 18 the first publication found was from 1989, the only of the year and it is interesting to note that in this document the term "green wall" does not refer specifically to outdoor vertical greenery systems. In fact in this paper, and the three works published in 1995, 1998 and 2002, this term has no scientific use, assuming the meaning of the "barrier function" that parks and urban greenery can fulfil in the city. Even if those papers do not present the specific topic analysed in this document, it is interesting to maintain them in the analysis since they are proof of the evolution of the "green wall" concept.

The first publication clearly referring to vertical greenery systems was in 2003, dealing with the decontamination of pollution in urban areas by green walls with nitrogen-dioxide-philic plants. This can be considered the first document in which the term "green wall" is used properly accounting outdoor vertical greenery systems.

Looking at the total timespan, three different periods of evolution in number of publications can be clearly identified: (1) the initial research from 1989 to 2009, characterised by a very low number of publications, (2) the developing phase, going from 2010 to 2015 and the (3) flourishing phase, that starts in 2016 and continue till nowadays. From 1989 to 2009, the publication number was around 1,4 documents. In 2010 publications rose to 7 and from 2011 the trend slowly increased till 2015 with 15 publications. In 2016 contributions duplicated respect to the previous year and the rise continued until 2019 with 52 publications, the highest number since 1989. Since then documents slowly decreased to 37 in 2020 but reached 49 in 2021, the second most productive year. In the current year, and precisely in the first two months of 2022, we can already see 12 publications. So, we can assume that the literature produced in the identified developing period built the academic basis to launch a flourishing field of research considering the dramatic increase of works from 2016. We think that relevance in this context may have the consideration of the various international programmes and incentives encouraging green solutions since 2015. We can see that the period 2016-2022 contributed to more than 78% of the total number of publications on the topic of outdoor VGS since the first publication in 1989. The scientific production of the first two month of the current year, in particular, equals the scientific production of the year 2021

and 2013. A particularly interesting issue could be investigated according to the peak of publications in 2012, probably due to some important research's results in the previous years. Since the first document found in the literature specifically dealing with VGS, which was published in 2003, results reveal a year-to-year growth in the number of documents, highlighting the rise of awareness and interest among the scientific community.
From the first document the annual growth rate of publication is 19,6%. Annual scientific production is shown in Fig.2.

2.2.5 Type of publications and sources

From the analysis of the type of publication it can be seen that almost 62% of the total 345 documents are articles, with an amount of 230 documents: 217, the large majority, published in Journals, 7 in Trade Journals and 6 in Book Series. Conference papers represent 20% of the analysed literature with 85 documents: 71 exposed in Conference Proceedings, 12 published in Book Series and 2 in Journals. On the other hand, there is a much lower number of Reviews with 14 documents and Book Chapters, just 16 documents. Furthermore, Reviews have all been published in the period 2014-2022. It can be argued that the need for systematic knowledge about outdoor VGS is a very recent issue. Accounting to the language, 337 documents, more than 97%, are published in english, taking into account the international nature of academic sources, while there is a scarce minority in german (dn=4), chinese (dn=2), italian (dn=1), japanese (dn=2) and portuguese (dn=1). The main source titles in which documents are published are Buildings and Environment with 22 publications, more than 6%, followed by Energy and Buildings with 15 publications representing more than 4% , Urban Forestry And Urban Greening and Acta Horticulturae, both with 14 documents, Iop Conference Series Materials Science And Engineering and Ecological Engineering with both 9 documents, Sustainability Switzerland with 8 documents, Energy Procedia and Iop Conference Series Earth And Environmental Science, both with 7 documents. From the total 183 sources of the bibliographic portfolio, 158, more than 86% have just one or two publications referring to the topic of outdoor vertical greenery systems. This is relevant information suggesting the multi- and inter-didciplinarity of the present topic.

2.2.6 Subject areas and journals

According to Scopus's subject areas categories, the highest percentage corresponds to Environmental Science with 160 documents (46,4%) followed by Engineering with 155 documents. These two subject areas include more than 91% of the total bibliographic portfolio.

Then there is Social Science with 69 documents, Agricultural and Biological Science with 60 documents and Energy with 54 documents. From this emerges the multidisciplinarity of the research field that includes scientific and social studies.

Moreover, it is interesting to note how subject areas had changed over time considering the three time slices previously identified. In the period 1898-2009 it can be seen a balanced situation that already proves the multidisciplinary nature of the vertical greenery systems application in the urban environment. Although the scarce number in publications (dn=10), it can be stated that at the very beginning of its evolution the field of research belonged mainly to the scientific sector. In fact, Environmental Science has the major number of documents (dn=3), followed by Biochemistry (dn=2), Genetics and Molecular Biology (dn=2), Chemical Engineering (dn=2), Engineering (dn=2) and Immunology and Microbiology (dn=2).

Enlarging the considered timespan to 2016 a totally new scenario emerges. In fact, despite the confirmation of Environmental Science (dn=47) as major area of interest and Engineering (dn=42) as second one, Social Science occupies the third position with 28 documents, exactly 27 more then the first period with an average of publication of 3,9 documents per year followed by Agricultural and Biological Sciences with 20 documents. Moreover, in this period appear for the first time publication in other subject areas such as Energy (dn=9), Physics and Astronomy (dn=9), Physics and Astronomy (dn=9), Medicine (dn=7), Arts and Humanities (dn=6), Immunology and Microbiology (dn=5) and Biochemistry, Genetics and Molecular Biology (dn=4).

It can be assessed that the period 2010 - 2016 was undoubtedly the development phase that enriched the research field in terms of themes and areas explored.

With these results, the interaction between the topics can be confirmed, such as the multidisciplinary research carried out within the urban greening topic. This statement confirmed the findings of Chafèr et al. (2021) accounting for urban greenery research field situations and vertical greenery systems in particular. When talking about greenery systems and/or the built environment, the synergy between different fields of study can be seen, from engineering to arts and humanities through business and management. The relevant fluctuation of interest in Social Science can be considered as a proof in literature of the multi- and inter-disciplinarity that characterised the process of "renaturation" in cities. A process that engage technical, environmental and social science, recognised framewok of the urban ecology field of research (Verma et al., 2020).

2.2.7 Keywords analysis

As argued in the work of A. Darko (2019), the analysis of Author's keywords in bibliometric research is a fundamental step

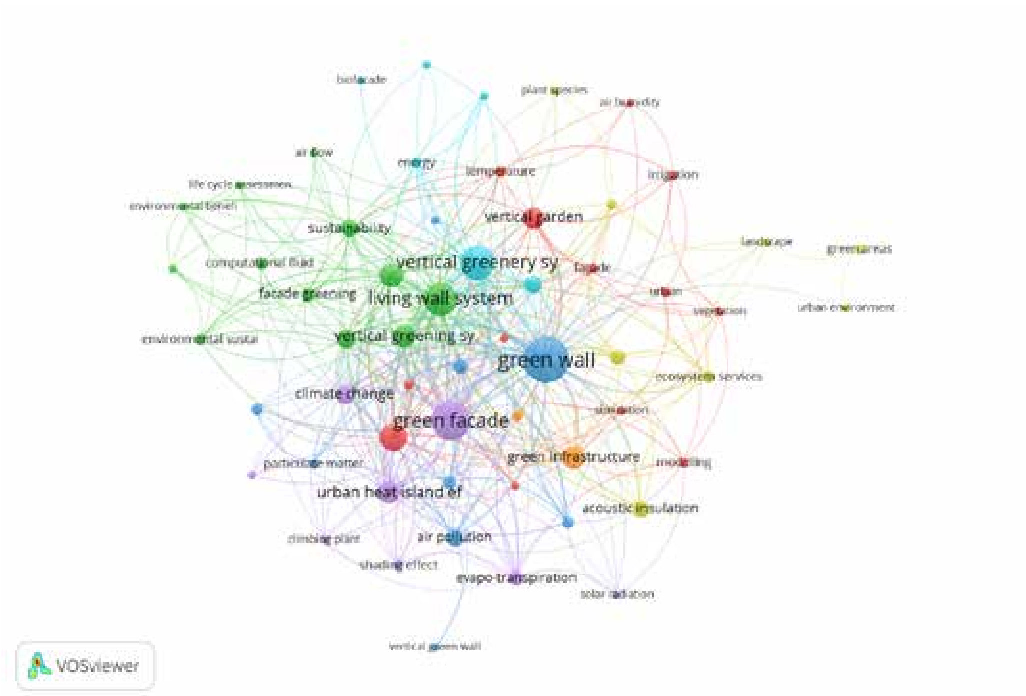


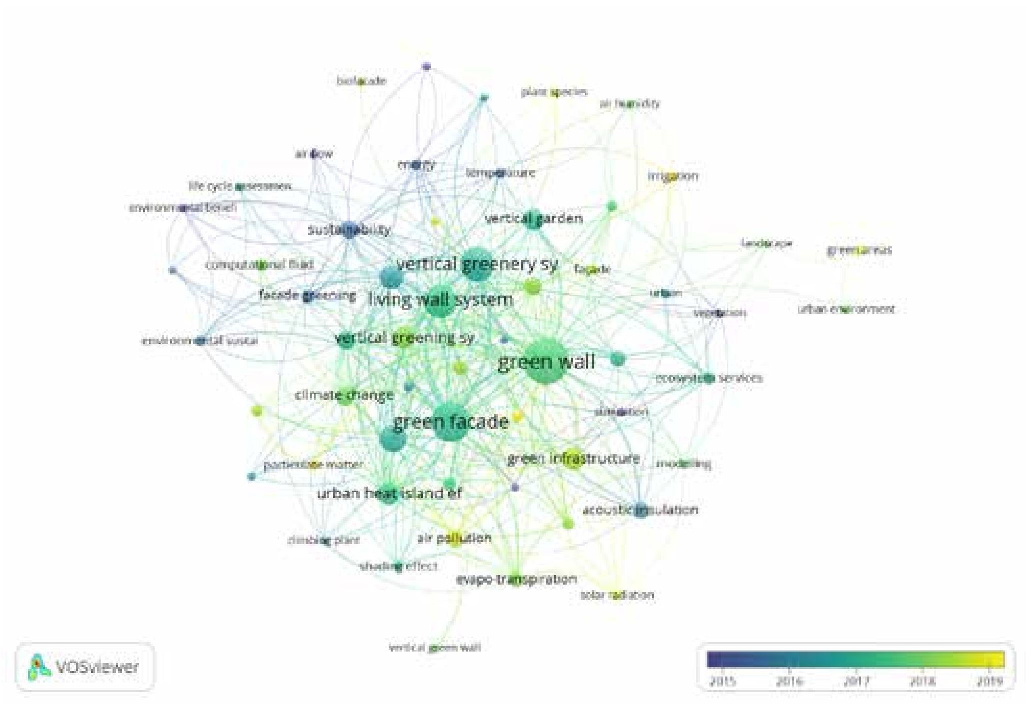
Figure 19. Network of the Author's keywords. Keywords with at least three occurrence in the whole bibliographic portfolio analysed for the time frame 1989-2022.

to outline topics and trends in a specific research field.

To set the creation of bibliometric maps, Author's keywords metadata network is imported in VOSviewer software from Biblioshiny, obtaining an amount of 826 terms. To obtain a correct database, a thesaurus file was applied, manually eliminating synonyms, singulars or unknown words that have never been found in the initial keywords research. Then, 663 keywords are reached. An occurrence limit criterion of 3 is set to obtain a visualisation of the most frequently used author keywords (present in at least 3 different documents). In this way we obtain a network describing the relationships between the 59 most common keywords found in the literature Figure 19. Fourteen different terms referring to vertical greenery systems nomenclature can be found. The most cited keywords in the field of outdoor vertical greenery systems are "green wall" (kwn=77) and "green facade" (kwn=57). This result is predictable and accertate the fact that these are the principal terms indicating the typology of outdoor vertical greenery systems. Then there are “vertical greenery systems (vgs)” (kwn=44), “living wall systems” (kwn=39), “vertical greening systems” (kwn=20) and “vertical garden” (kwn=17). According to the nomenclature stated by Manso et al. (2015), this first result can demonstrate a major research commitment in the field of living wall (green wall and living wall systems) then in green facade. This can depend on the fact that living wall systems demonstrated higher performance than green facades (Ottelé, 2013), offering a more interesting field of research and application for building energy efficiency optimisation in particular (Pan and Chu, 2020).

The terms “vertical greenery systems” (kwn=12), “vertical greening systems” (kwn=11) and “vertical garden” (kwn=11) are general ones that include all the systems typologies (Radic et al., 2019). They achieved a discrete value of occurrence. It is anyway important to notice that in the works of one of the most cited authors

Figure 20. Temporal development. Author’s keywords temporal development for the time frame 1989-2021.



in the topic, K. Perini, the term "vertical greening systems" is used to precisely indicate direct or indirect green facade (Perini et al., 2011, Ottelé et al., 2011). The ambiguity in the nomenclature of typology of VGS is a very recent recognised topic (Radic et al., 2019). This situation could reflect the relative newness of the vertical greenery sustems field of research.
Other terms with a substantially lower occurrence are interconnected with these central key terms. In particular, it is interesting to notice very recent terms are "green screen facade" (kwn=1) that occurs in the paper of Vasquez et al. (2020) and "modular living wall" in 2021 (Fig.4). These two terms are synonymous with green facade and green wall respectively. The presence of new terms that refer to a specific typology of vertical greenery systems could demonstrate an increasing interest in sectorize the research field. This is an endeavour that can contribute to develop a clear knowledge about the differences that characterise each system typology.

All the other mapped keywords have an occurrence lower than 21. The analysis of the Author's keywords can give an immediate look to the main areas of research analysed regarding the vertical greening benefits in urban context.
It can be seen that "thermal benefits" (kwn=28) is the "thematic" keyword with the highest occurrence, indicating a relevant common interest in the field of thermal comfort improvement in urban context. Other most relevant keywords are "energy savings" (kwn=21) and "urban heat island effect" (kwn=20). This is the thematic keyword with the highest number of connections with other keywords (kwl=26). This informs about the wide investigation of the performance of outdoor vertical greenery systems in response to urban temperature increase.
Thus, the high occurrence of "thermal benefits", "energy savings" and "urban heat island effect" clearly outline the issues that can be defined as the fields of major interest in the literature: the mitigation action of vertical greenery systems in the urban microclimate, their performances in buildings thermal comfort and their thermal insulation properties that can allow a cut off of cooling and heat systems (Pan et al., 2020).

As can be seen from Figure 20, keywords that mostly appear in very recent years (from 2019) are "particulate matter", relating to the action of vegetation in the absorption and mitigation of air pollutants deriving from transport pollution, "plant species" (n=3), with a significant relation to the insulation effect and selection in vertical greenery systems. This is a topic investigated mainly in botanical fields and still at the beginnings in vertical greenery systems research (Reyhani et al., 2023). Then, "irrigation", dealing with a technical aspect that is a crucial issue cosnidering the high water consuming nature of vertical greenery systems (Oquendo di Cosola et al., 2019).

It is interesting to notice the absence of keywords accounting to the social and well-being benefits related to outdoor

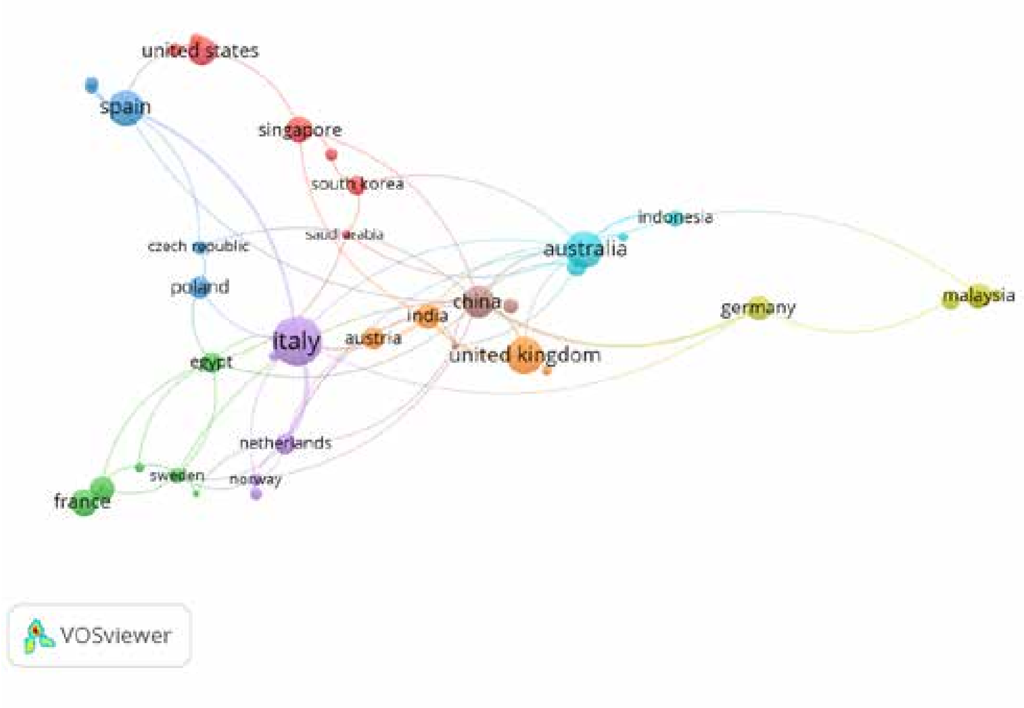


Figure 21. Geographical distriution. Co-authorship relations within countries for the analysed bibliographic portfolio.

VGS, stating a clear lack of interest and knowledge in the research field.
The mapped keywords are subdivided by the software VOSViewer in 7 clusters (Figure 21). They are useful to identify the principal area in which research on outdoor VGS is divided by.

Cluster #1 is one of the most relevant clusters, containing 13 keywords and dealing with thermal performance and urban temperature, as can be concluded from the terms "thermal benefits", "temperature" (n=5) and "mean radiant temperature" (n=3).
Cluster #2, the second most relevant one, contains 12 keywords and according to the presence of terms such as "energy savings" (n=21), "environmental benefits" (n=3) and "environmental sustainability" (n=3), deals with the environmental burden of the VGS.

Cluster #3 deals with air pollution mitigation in urban environments, containing keywords such as "particulate matter" (n=4), "air pollution" (n=10) and "street canyon" (n=6).

Cluster #4 includes terms such as “insulation effect” (n=5), “acoustic insulation” (n=11), “buildings” (n=9) “ecosystem services” (n=6) and “plant species” (n=3), particularly focusing on the vegetation specific contribution to urban noise absorbtion.

Cluster #5 includes terms such as “urban heat island effect” (n=20), “climate change” (n=14), “evapo-transpiration” (n=9) and “shading effect” (n=5), focusing on vegetation functions useful to mitigate urban temperature peaks.

Cluster #6 contains “cooling effect”, “sound absorption” and “temperature reduction”, merging the topics of the other clusters.

Finally, **Cluster #7** is a very little cluster, composed of just two terms, “green infrastructure” (n=19) and “urban greening” (n=9), general terms in which vertical greenery systems are typologically inserted.

It can be seen that every cluster has a leading term that stands out from the network. It is interesting to notice that for the majority of the clusters these leading terms are keywords referring to different vertical greenery systems nomenclature typology. This lets suggest that specific typologies are more investigated in specific fields and strictly related to them.
As a general observation, clusters do not present a clear thematic characterisation as the presence of similar keywords in different clusters can suggest. This aspect can be interpreted as a sign of the multidisciplinarity and interrelation of issues of the research field. From these results can be observed that also the newness of the topic leads to a lacking of in depth research topics' sectorialisation.
Looking at the temporal evolution of the Author's keywords and topics (Fig.x), it can be clearly noticed that terms contained in **Cluster #2** are generally older than the others, having an average year of publication around 2014. It can be asserted that since that year, research on sustainability issues drastically decreased, showing today a lack in the field of outdoor vertical greenery systems.

2.2.8 Geographic distribution of the publications

Outdoor vertical greenery systems have a globally broader research. Contributions can be found in 60 countries, representing five continents (Figure 21). It can be noticed that there are five main countries that have a significant production of documents on the outdoor vertical greenery systems theme. Considering the total scientific production of each country, Italy is the most productive country (dn=50) reaching almost 14,5% of the total number of publications. Australia and the United Kingdom are the second most productive countries with 28 publications each, almost half the scientific production of Italy. Then there is Spain with 26 documents, followed by China (dn=20), United States (dn=18)

France (dn=15), Singapore (dn=14), Japan (dn=13). Germany, Malaysia and India have 12 documents each. The rest of the countries present less than 10 documents. It can be observed that the European scientific production represents almost 46,5% of the worldwide one. Furthermore, it is relevant to note that the ten most productive
countries have produced more than half the worldwide scientific production reaching almost 65%.

Figure 22 shows the relations derived from co-autorhip collaborations between nations. Links between countries indicate a cooperative relationship, the thicker the connection, the stronger the cooperation between the two countries in terms of the number of co-authored contributions.
China is the country with the wider research network, linking to 14 different countries: Australia, Spain, United Kingdom, Germany, India, Netherlands, Singapore, Hong Kong, Egypt, the Czech Republic and more recent nodes such as Norway (2019), Sweden (2020) and Vietnam (2021). China has an average of link strength, i.e. documents co-authored, of 1 except the ones with Australia, co-authoring 2 documents, the UK, 3 documents and Germany, 4 documents, the strongest link in its research network.
Accounting for the total number of publications of China and the ones co-authored with foreign authors, it can be stated that research in China is strongly international. In fact China collaborates with other countries for almost 78% of its research on outdoor vertical greenery systems topics. Australia has the second wider network of collaborations, linking to the UK, China, Hong Kong, India, Netherlands, Sudi Arabia, South Korea, Malaysia, Norway (2019) and Vietnam (2020). Despite this, links are not very strong, in fact Australia has just 1 co-authored document for each country, with the exception of China with 2 documents. This could be an evidence of a non-continuative work of research with research groups and affiliations. In general it can be stated that Australia collaborates with other countries for 50% of its research on the outdoor vertical greenery systems, thus its research is highly international.
Regarding the collaboration with other countries the third country in terms of network width is Italy, forming 9 links in total with Poland, Egypt, India, Austria, Netherlands, Czech republic, Spain and Norway. Also in this case the average of link strength is about 1, with an exception. The strongest link is with Nederlands, this nation produced 6 documents in collaboration with Italy over its total 8 documents on the topic of outdoor vertical greenery systems. Italy collaborates with other countries for just 29% of its research on outdoor vertical greenery systems topic. Despite the high number of publications, this country reveals very little internationality in comparison to China and Australia.

Figure 22 shows the temporal development of the research on the topic in each country. The chronological distribution follows a colour index from blue to yellow

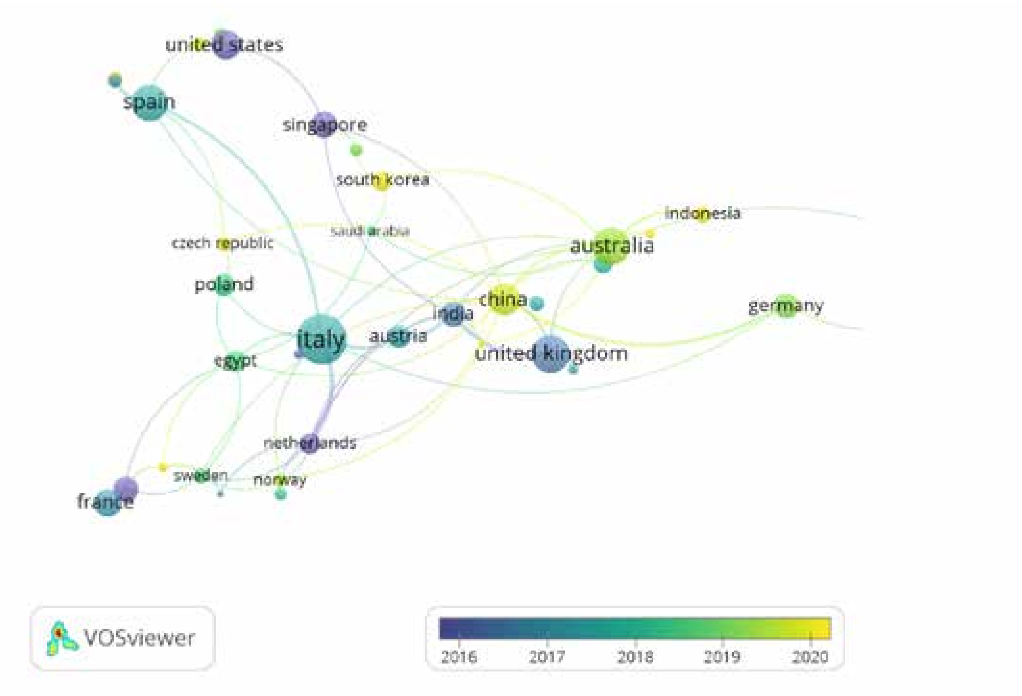


Figure 22. Temporal development. Temporal development of co-authorship relations within countries for the analysed bibliographic portfolio ranging from 1989 to 2022.

indicating the average year of publication. The most recent research is carried out in Vietnam (2021), Denmark (2020), Sweden (2020) and Norway (2019), countries that started the research on the outdoor vertical greenery systems in a very recent time. As can be seen from Figure 22 countries that have published on outdoor vertical greenery systems for a longer time are Japan, Singapore and Canada, whose average publication year is 2014, followed by the United States and Netherlands whose average publication year is around 2015. According to the publication trend explained in 2.2.4 it can be noticed that the average publication year of any country is between 2014 - 2021, mainly including the most productive time slice (from 2017).

It can be seen that Italy and the UK, the most productive countries, have no relations, in fact no research has been conducted in collaboration between the research group of the two nations. In general, it is evident that Italy has relations with countries with a very low number of publications and links between them are very weak, generally exhibiting just 1 co-authored document. As for Australia,

this data can be read as a signal of non-continuative research collaboration.
A singular result, looking at the network relations between countries (Figure 21 and Figure 22), is the isolated position of Jordan, Malaysia, Turkey and Canada from the rest of the nodes. Malaysia, the most productive in this group (12), is the country that has co-authored documents with all the others seamingly creating a loop of collaboration. Only Malaysia and Canada have co-author relations with other countries, respectively with Australia and Germany. From this it can be suggested that Malaysia and Canada have basically a national research setting, they usually do not collaborate with other countries on the outdoor vertical greenery systems topic.

Table 1. Authors. Most productive authors on the topic of outdoor vertical greenery systems in outdoor environment.

Author	*Institution*	*Country*	*Documents search*	*Total documents*
schettini e.	Università degli studi di Bari	Italy	13	84
vox g.	Università degli studi di Bari	Italy	13	81
perini k.	Università degli studi di Genova	Italy	11	39
blanco i.	Università del Salento	Italy	9	27
coma j.	Universitat de Leida	Spain	9	28
pérez g.	Universitat de Leida	Spain	9	48
cabeza l.f.	Universitat de Leida	Spain	8	170
convertino f.	Università degli studi del Molise	Italy	6	12
deletic a.	University of New South Wales	Australia	6	71
korjenic a.	University of Belgrade	Serbia	6	19
ottelé m.	Technische Universiteit Delft	Netherlands	6	114
urrestarazu m.	Universidad de Almería	Spain	6	122
wong n.h.	National University of Singapore	Singapore	6	235
cameron r.w.f.	Vellore Institute of Technology	India	5	67
ghosh s.	University of Kansas	USA	5	80

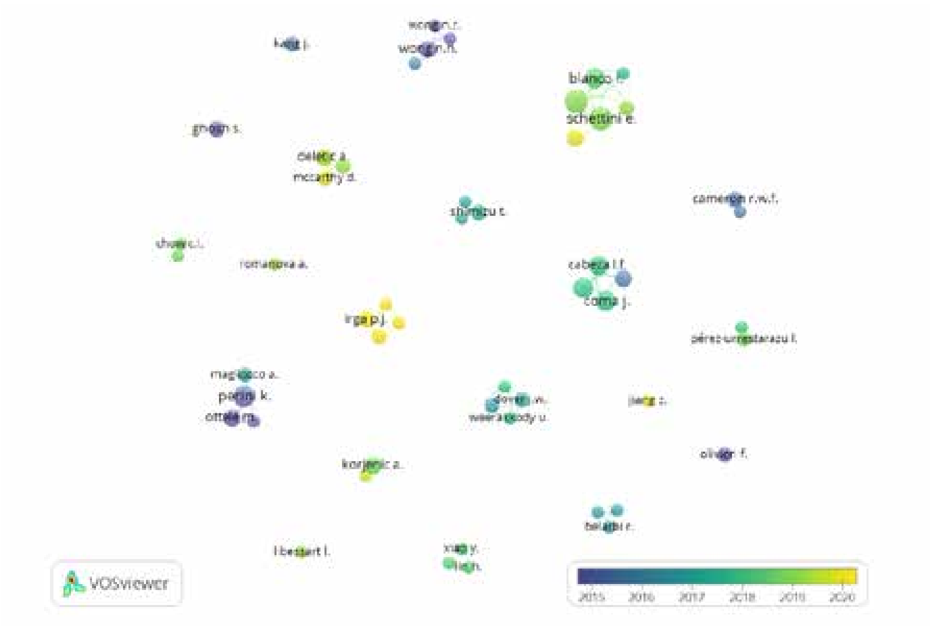


Figure 23. Temporal development. Authors' collaborations distribution in time.

2.2.9 Analysis of authors

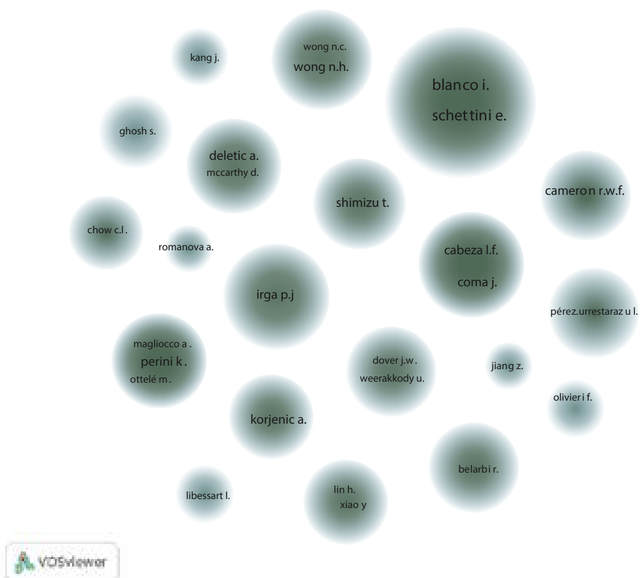
In the development of a bibliometrics analysis, it is commonplace to see collaborations among authors in academic research. For this co-authorship analysis, the minimum number of articles published by an author has been set to three in VOSviewer. This means that every author who appears in Figure 23 published at least three or more articles in this field.

According to Scopus databases, E. Schettini and G. Vox, both from the Università di Bari, are the most productive authors in the topic of outdoor vertical greenery systems with a total of 13 documents each, producing 3,8% of the total literature on the topic. Other authors with significant contributions to the research community on the topic of vertical greenery systems for the urban environment include K. Perini, from Università di Genova, whose works represent 3,2% of the total publications, with 11 documents. Then there are I. Bianco, from Università del Salento, J. Coma and G. Perez, both from Universitat de Lleida, with 9 documents each , reaching 2,8%. Then, L. F. Cabeza, from the same university, with 8 documents (2,3%). Moreover, Table 1 shows the top fifteen authors with a greater amount of publications in the research topic. The table shows the published documents on

the topic of outdoor vertical greenery systems in relation to the total number of documents of each author considered. This comparison highlights the weight of the analysed topic on the whole academic production for the authors.
In general it can be seen the central role of the Univeristà di Bari in the development of the research field of the outdoor vertical greenery systems topic. The first paper of this affiliation was published in 2017 by G. Vox et al. and the last one in 2020 by F. Convertino et al.

As can be seen from Figure 23, the wider network of collaboration within worldwide authors is between Università di Bari (Italy) and Università del Salento (Italy), creating a network of six authors, followed by the network of the Universitat de Leida (Spain), with four authors, and the network between the Università degli Studi di Genova (Italy) and the Technische Universiteit Delft (Netherlands). The most recent and productive group of research is the one from the University of Technology of Sydney (Australia).
As can be seen from Figure 23, the worldwide scenario is characterised by a complex system of research relationships (nodes groups) and the majority of these have a very recent activity (yellow nodes groups), with an average publication year between 2019 and 2020. Moreover, a relevant part of these new groups co-authored just one publication on the outdoor vertical greenery systems. This aspect can indicate the early birth of new

Figure 24. Density visualisation. Most productive authors with normalised average number of citations.



groups of researchers interested in the outdoor vertical greenery systems and so a worldwide diffusion and growth of the research topic.

Through the density visualisation (Figure 24) it can be clearly observed the particular relevance of three networks of authors. The most productive one is composed by (1) Schettini, Vox, Blanco, Convertino, Scarascia Mugnozza and Campiotti creating a network between Università di Genova, Università di Bari and Università di Napoli, the second composed by (2) Perez, Cabeza, Coma and Urrestarazu linking the Universitat de Lleida and the Universidad de Almería, and the third group composed by (3) Perini, Ottelé, Magliocco and Haas, creating a network between the Università di Genova and Technische Universiteit Delft.
Moreover, considering the authors' citations referring to the current bibliometrics portfolio it can be seen that N. H. Wong, from the University of Singapore, is the author with the highest number of citations, reaching 538, followed by K. Perini with 481 and L. F. Cabeza, J. Coma and G. Pèrez, with 436 citations each. It is relevant to note that N. H. Wong overcomes other authors despite the discrete number of publications (nd=6), suggesting the scientific relevance of his contributions.

Nevertheless, besides the citations analysis, normalised citations analysis has to be done in order to identify current hotspots of scientific relevance in researchers' production. Normalised citations' number equals the number of citations of a document divided by the average number of citations of all documents published in the same year included in the bibliometrics portfolio. In this case normalisation equalises disparities between authors working for different time periods, in fact older documents have had more time to receive citations than more recent documents. Through this analysis it can be noticed that the previous scenario radically changes. Other authors emerged such as A. Deletic, with the highest normalised citations' numbers of 21,33, followed by L. F. Cabeza and J. Coma with 19,84 each and E. Schettini with 18,48. Then there are K. Perini with 14,53, N.H. Wong with 13,51, J. W. Dover with 12,25 and I. Blanco with 11,90. Considering the short period of publication about outdoor vertical greenery systems of A. Deletic (2017-2022) the average citation achieved shows the relevance of the research work in the considered academic topic.
According to these data and looking at the co-authorship relation it can be noticed the emergence of three relevant authors groups: (1) one composed by Deletic, MacCarthy and Prodanovic, one by (2) Dover, Weeradokky, Mitchell, Reiling and one composed by (3) Wong, Wong, Tan and Tan. From this it can be assessed that these six researchers groups developed very relevant works for the academic community concerning the discussed topic.

2.2.10
Most influential publications

The analysis of the most influential publications for a specific topic followed as a continuation and deepening of authors' analysis findings. This analysis is fundamental to establish which have been the contributions that have acted as milestones in the development of a specific research field (Figure 25). The first part of the analysis considers the five contributions that received the highest number of citations since their publication.

For the analysed period 1989-2022, the first most cited document is "Vertical greening systems and the effect on air flow and temperature on the building envelope", by K. Perini et al. (2011), published in Building and environment, with 263 citations. This document deals with thermal performances and provides an analysis and experimental approach to evaluate the influence of wind velocity and its effect on the thermal resistance of different types of green facades and living wall systems at the building level.

The second and third most cited papers are works of Wong N. H. et al. (2009; 2010). The first is titled "Energy simulation of vertical greenery systems" and is published in Energy and Buildings, with 156 citations. This document concerns the simulation of the effects of a VGS on the temperature and the energy consumption of buildings. It states that 100% of greenery coverage from vertical greenery systems is effective in lowering the mean radiant temperature of a glass facade building and, furthermore, that to lower the energy cooling load significantly, the shading coefficient of plant species has to be low. This work highlights that the thermal calculation of the envelope thermal transfer value shows a linear correlation between shading coefficient and leaf area index. The second documents "Acoustics evaluation of vertical greenery systems for building walls", published in Energy and Buildings, with 154 citations. It has to objectives: the first involves the evaluation of the acoustics impacts of eight different vertical greenery systems on the insertion loss of building walls. The experiment shows a stronger attenuation at low to middle frequencies due to the absorbing effect of substrate while a smaller attenuation is observed at high frequencies due to scattering from greenery surfaces. The second objective is to determine the sound absorption coefficient of the vertical greenery systems constructed in a reverberation chamber, which is found to have one of the highest values compared with other building materials and furnishings. Furthermore the work states that, as frequencies increase, the sound absorption coefficient increases and observes that the sound absorption coefficient increases with greater greenery coverage.
The fourth most cited paper is "Vertical greenery systems for energy savings in buildings: A comparative study between green walls and green facades" (2017), by J. Coma et al. and published in Buildings and Environment, with 148 citations.

The study compares at real scale the thermal performance of two different vertical greenery systems implemented in experimental houses-like cubicles for both cooling and heating periods. This work reports results of an on-site experiment. In fact, a double-skin green facade has been installed in the first cubicle that uses deciduous creeper plants, while the second one is designed with green walls made with evergreen species. A third cubicle without any green coverage is used as reference. Two different types of experiments have been carried out to test the performance of the house- like-cubicles. One consists of controlling the indoor ambient temperature providing heating or cooling to maintain the desired comfort conditions. The second is to study the thermal response of the construction system disconnecting the heating, the ventilation and the air conditioning systems. Results showed a high potential for energy savings during the cooling season for the green wall and double-skin green facade in comparison to the reference system, while, for heating periods no extra energy consumption has been observed for evergreen systems.

The fifth most cited paper is "What's 'cool' in the world of green façades? How plant choice influences the cooling properties of green walls" (2014), by R.W.F. Cameron et al. and published in Buildings and Environment, with 145 citations. The research investigated green façades using wall shrubs and climbing plants to reduce air temperature adjacent to, and surface temperatures of, brick walls. Artificial wall sections have been used to provide replicated data sets in both outdoor and controlled environmental conditions. During periods of high solar irradiance, the presence of *Prunus laurocerasus* plants placed against walls significantly reduced air and surface temperatures compared to blank walls, but also in comparison to excised plant sections. The work highlights that largest temperature differentials have been recorded in mid-late afternoon, where air adjacent to vegetated walls was cooler than non-vegetated walls. The contribution focuses on plant species performances, stating that Prunus provided significant wall cooling in controlled environment studies, but little effective in surface cooling capacity when compared to other species such as Stachys and Hedera, that provide >7.0°C cooling. The work shows that when evaluated on a per leaf area basis other plant species demonstrated greater cooling potential, with *Fuchsia, Jasminum* and *Lonicera* out-performing others. From this the study assesses that different species varied in their cooling capacity and moreover that the mechanisms for providing wall cooling varied between species. In fact, *Fuchsia* promoted evapo-transpiration cooling, whereas shade cooling was more important in *Jasminum* and *Lonicera*. The work clearly states that plant physiology and leaf area/morphology are characteristics that should be considered in vertical greenery systems design to maximise buildings cooling performance.

As introduced in 2.2.7, thermal performance and thermal building conditions are demonstrated to be the main topics of

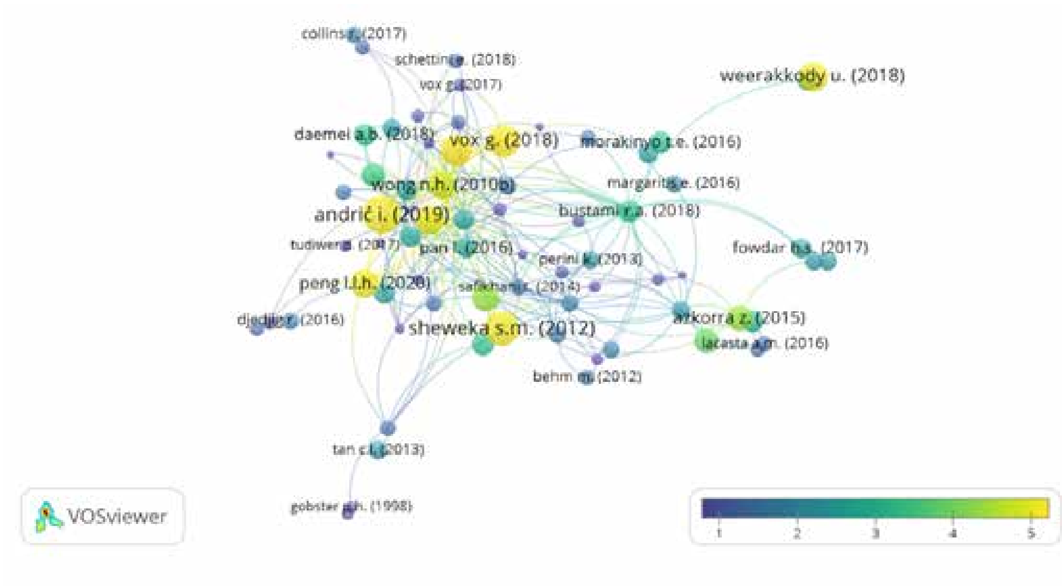


Figure 25. Relevant publications. Network of the 85 most cited papers within the analysed bibliographic portfolio with normalised average citations number.

interest in outdoor vertical greenery systems research and the relevance of these papers prove it. Four of the five most relevant publications develop studies related to outdoor vertical greenery systems benefits and influence on temperature control and variation. Moreover, it is interesting to note that the third document deals with acoustic insulation, a theme not particularly present according to keywords analysis. From this it can be assumed that the relevant position of this paper depends on the little presence of publication on the acoustic issue, achieving a real milestone role in the vertical greenery systems acoustic function investigation. A similar hypothesis can be done referring to the fifth document. In fact, as seen from the keywords analysis, green facades are the outdoor vertical greenery systems less investigated. Moreover, plant species characterisation and performance evaluation in vertical greenery systems thermal control is barely treated in literature, making this contribution one of the most complete and exhaustive on the topic.

Beside the identification of milestones in scientific production on the discussed topic, it is significant to determine which publications obtained relevant consensus in the academic community. To find and visualise them is necessary to normalised the number of citations per document.

In this case it can be seen from Figure 25 that the most influential publication is “A review of climate change implications for the built environment: Impacts, mitigation measures and associated challenges in developed and developing countries” by Ivan Andrić et al. (2019), published in the Journal of Cleaner Production. The document is an interdisciplinary review that summarises and critically analyses the literature regarding the nexus between climate change and the built environment, its associated impacts, and the proposed mitigation measures and challenges for their implementation, dealing with the need for a development of the vertical greenery systems technology. This review counts just 41 citations but an average number of citations per year equals to 7.78, a quite high value considering that the majority of the mapped papers have a number equal or lower than 2. For this reason this paper can be defined as the most influential research output in the topic of outdoor vertical greenery systems. The high relevance of a review paper can be seen as a common necessity of a body of knowledge on the state of the art of vertical greenery systems research from the academic community.

The second most relevant contribution with normalised citations is “The effect of a living wall system designated for greywater treatment on the hygrothermal performance of the facade” (2022), by H. Alsaad et al. and published in Energy and Buildings with a normalised citation number of 7,00. In this work living walls are investigated as decentralised stand-alone systems to treat greywater locally at the building level, accounting for the considerable impact on the hygrothermal performance of the facade. Considering the difficulty to represent complex entities such as plants in the typical simulation tools used for heat and moisture transport, this study suggests a new approach to tackle this challenge by coupling two tools: ENVI-Met, used to simulate the impact of the plants to determine the local environmental parameters at the living wall, and Delphin, used to conduct the hygrothermal simulations using the local parameters calculated by ENVI-Met. Four different wall constructions have been investigated in this study: an uninsulated brick wall, a precast concrete plate, a sandy limestone wall, and a double-shell wall. The results showed that the living wall improved the exterior surface temperature and the heat flux through the wall. Furthermore, results show that the living wall did not increase the risk of moisture in the wall during winter and eliminated the risk of condensation.

The third most relevant paper with normalised data is the already mentioned Coma et al. (2017) that achieves an average number of citations of 6,51.

The fourth is “The Living Walls as an Approach for a Healthy Urban Environment” by Samar Sheweka et al. (2011), published in Energy Procedia and with an average citation number of

6,35. This research displays meanings, advantages and techniques of the living wall as part of a sustainable strategy for the urban environment, highlighting the relevant contribution of vertical greenery systems in environmental, social and economic benefits in the city. The research tackles the emergence of technology as a valuable part of the design process for facing climate change and energy crisis, introducing other ecological services such as urban agriculture, urban gardening, or aesthetical and recreational functions. As a peculiar observation, the contribution highlights how living walls are suitable in arid areas, as the circulating water on a vertical wall is less likely to evaporate than in horizontal gardens.

Finally, the fifth contribution is "Green façades to control wall surface temperature in buildings" (2018b) by Vox et al. and published in Buildings and Environment, with a normalised citations number of 6,04. According to the contribution, green façades can represent a sustainable solution for construction of new buildings and for retrofitting existing buildings, in order to reduce the energy demands of the cooling systems, to mitigate the urban heat island and to improve the thermal energy performance of buildings. Green façades can allow the physical shading of the building and promote evapotranspiration in summer, and increase the thermal insulation in winter. The work displays an experimental test carried out at the University of Bari (Italy) for two years. Three vertical walls, made with perforated bricks, were tested: two were covered with evergreen plants while the third wall was kept uncovered and used as control. Several climatic parameters concerning the walls and the ambient conditions were collected during the experimental test. Findings highlight that the daylight temperatures observed on the shielded walls during warm days were lower than the respective temperatures of the uncovered wall up to 9.0 °C. The nighttime temperatures during the cold days for the vegetated walls were higher than the respective temperatures of the control wall up to 3.5 °C. The work assesses that the thermal effects of the facades at daytime was driven by solar radiation, wind velocity and air relative humidity. Moreover, the study investigated vegetal component characteristics and responses: the long-term experimental test demonstrated that two particular plant species, *Pandorea jasminoides variegata* and *Rhyncospermum jasminoides*, are suitable for green façades in the Mediterranean climatic area. The particular aim of this work is to fill the gap in literature concerning the lack of data for all the seasons of the year. Hence it obtains a complete picture of the building thermal performance in the Mediterranean climate region.

From the analysis of these last five contributions it can be clearly seen the emergence of less discussed topics such as: water management, socio-economic contribution of vertical greenery systems in the urban environment and characteristic plant species phytology performance and modelling as vertical greenery systems components. From this, according to academic interest these topics can be clearly identified as future research directions

2.2.11 Knowledge gaps in research

Reviewing the papers related to the outdoor VGS topic in the period 1989–2022, it provided an in-depth discussion to summarise the contemporary mainstream research topics, identified research limitations and proposed future research directions.

The first knowledge gap identified in the current scientific topic state-of-the-art is related to the environmental impact of vertical greenery systems. Although most studies advocate the benefits of outdoor vertical greenery systems, very few of them deal with its environmental impact. As can be seen from Fig. x and Fig. x, environmental issues concerning outdoor vertical greenery systems are poorly investigated. Despite their application in urban context refurbishment, knowledge about the impact of vertical greenery systems life cycle and implementation of systems, components and materials are still at the very beginning. Moreover, life cycle thinking in the discussed research topic seems just related to environmental impact. Despite the well known economic endeavour represented by vertical greenery systems solution, life cycle costing is barely developed and proposed in literature and social life cycle assessment is totally ignored. From this it can be concluded that the life cycle profile of outdoor vertical greenery systems is a relevant gap in the research. Considering the increasing diffusion of life cycle thinking approach in more and more research, urban and industry sectors (Mirabella et al., 2019), this gap indes the dissemination and innovation of green technology, and VGS in particular.

The second knowledge gap is related to the real performance and benefits of outdoor vertical greenery systems. The large majority of studies deal with thermal performance and consequential energy savings. Instead, noise pollution reduction, air pollution mitigation and biodiversity enrichment issues are still little assessed.

This situation reflects the difficulty to quantify vertical greenery systems performances (Abhijith et al. 2017). Indeed, thermal action of vertical greenery systems can be more easily defined considering the energy and money savings in cooling and heating systems of buildings, as some studies declair. In these cases quantifiable benefits are more clearly identified. Vertical greenery systems actions of pollution mitigation and biodiversity improvement are still largely unknown since systematic empirical data collection has not been done. Scarcely investigated are also the correlation between these benefits and specific plant species, a topic that could collaborate to redefine the function and role of vegetation in cities. This type of investigation requires a high level of interdisciplinary collaboration between different research fields. The investigation of foliage morphology and

plants phythology in response to air pollutants capture and microclimatic regulation is little tested especially in on site experiments.
As a complex process of definition and quantification, the difficulty to determine biodiversity and social impact and benefits is strictly related to the identification and construction of quantitative indicators. This situation confirms the assessment of Cheng et al. (2021) in reference to cultural ecosystem services offered by green technology and vertical greenery systems in particular.

The third gap is related to outdoor vertical greenery systems social and well-being benefits. In this case it is interesting to notice that, despite the academic sector having shown little interest in the topic, urban planning, design studios and industries frequently advocate the beneficial action of vertical greenery systems on the urban environment from a psychological point of view. Hence, empirical results on social benefits in the urban context is identifed as a research gap. Nevertheless, it can be assessed that this aspect is getting increasing relevance in urban greenery academic research (Goel et al., 2022). In fact, more recent studies deal with city sustainability strategies through adoption of outdoor vertical greenery systems solutions and the spread of biophilic concepts fosters the adoption of flexible greenery solutions in the urban environment. So it is necessary to deepen the understanding and definition of the principles through which vertical greenery systems can transform and influence the interaction between citizens, natural processes and urban spaces.

The fourth gap is related to material research of the outdoor vertical greenery systems structure and components. This issue is strictly related to the system's sustainability. Considering growing media in particular, circular economy approach is now little investigated and research commitment is still not sufficiently diffuse to offer specific applicable solutions in any country. In fact, to obtain a sustainable growing media it is strictly necessary to look at local production and supply chain (Barrett et al., 2019). Moreover, material research for structure components is almost totally lacking, except for the works of Manso et al. (2018) and Cortez et al. (2020), both focusing on circular economy and systemic approach.

2.2.12 Outlining future directions

The bibliometric analysis carried out suggests that until recently most research emphasis has been placed on vertical greenery systems thermal performances. However, since the first appearance of these systems in the literature the research into their use has shown a continuous growth, particularly increasing during the previous decade with the broadening of issues and topics related to outdoor vertical greenery systems. Furthermore, the aim of mitigating the effect of climate change in the urban environment, such as the urban heat island effect, has led to a focused exploration of the vertical greenery systems thermal isolation and cooling performances, with particular interest in related energy and money savings.

Based on the results of the review, there are three important topics for future research. The little attention paid to outdoor vertical greenery systems environmental impacts suggests the need to explore the life cycle of these systems. LCA methodology should be applied to assess the impact of these solutions, focusing on the construction phase and its contribution to both the entire life cycle of the vertical greenery systems and the energy balance. Through the adoption of LCA, it would be possible to investigate new materials, dramatically improving the environmental performance of vertical greenery systems components and functions. Since these issues have not been investigated in much depth, this is a promising field of innovation for vertical greenery systems, regarding many opportunities for application with the re-use of local manufacturing by-products and as yet unvalorised resources.. This is an interesting direction for the research in this field that will engage vertical greenery systems experimentation in the circular economy and systemic design approaches (Bistagnino, 2016).

In addition, more in-depth study into vertical greenery systems air pollution mitigation and biodiversity enrichment would highlight the strongly multi-functional nature of these systems, capable of an extremely high flexibility to solve critical urban conditions. Considering the level of complexity of the topics taken into account and the worldwide collaboration networks, it is necessary to improve international collaboration in the outdoor vertical greenery systems research field. This would allow the collection of data on different environmental conditions and climatic zones, which highly influence the performance of these systems in pollutant removal and biodiversity support. Focusing on biodiversity, it is crucial to improve the commitment in vertical greenery systems research to identifying guidelines and strategies that could aid the design of projects involved in urban fauna and flora enrichment and support.

The city structure is a complex interrelationship of infrastructures and natural hotspots (Berthon et al., 2021) and vertical greenery systems could be a tool for studying, understanding and redefining the relationship between antropic and natural habitats (Francis and Lorimer, 2011). From this point of view, the diffusion of these systems could improve the data collection on the ecosystem services offered, promoting citizens' participation in the green transition of cities (Beatley, 2018). These community engagement actions are already used to foster social and ecological benefits in the urban environment, showing in practice the interrelationship between the well-being of people and nature (MICS, 2020).

Urban greenery offers the opportunity to mitigate the adverse effects of climate change and the urban heat island effect and thus generates important benefits from the perspective of human health and well-being. Considering the recent Covid-19 pandemic crisis and the subsequent common desire for a more nature-related daily life, this can be a promising field of investigation, which in recent years has already started to be the subject of academic interest (Collins et al., 2022; Pérez-Urrestarazu et al., 2021). Many projects and applications outside the academic world have already used outdoor vertical greenery systems as a solution for social and well-being benefits, often activating bottom-up approaches (Comino et. al, 2021).

In the future it could be useful to increase the collaboration and contamination between the research and design fields. Observation of the outcomes of real applications in the urban context could be a useful method of analysis in order to theorise principles and guidelines to improve human and urban vegetation interaction (Nesbitt et al., 2017).

The research on outdoor vertical greenery systems requires much greater investigation in terms of the multidisciplinary endeavour needed to face the complex issues of contemporary city contexts. The current global and European programmes sustaining the greening and resilience shift of the urban environment prove the necessity of empowering academic commitment on the theme. Furthermore, a cross-fertilisation between the research field, decision-makers and urban planning has to be encouraged and undertaken.

2.3 Real case studies analysis

In this section, we will explore real-world applications of vertical greenery systems to shed light on the various issues and topics that currently engage design practice. These practical examples will serve as case studies, offering insights into how vertical greenery is being used in urban environments and the challenges it seeks to address. By examining these real applications, we aim to provide a comprehensive view of the issues and considerations that designers are grappling with in their efforts to integrate vertical greenery into urban landscapes. This exploration will help us understand the evolving role of vertical greenery and the ongoing discourse in the field of design practice.

2.3.1 Cities that embrace nature

Urban settings offer a unique perspective for examining and observing the requirements and aspirations of modern society. Throughout the 20th century, there was a widespread phenomena of migration from rural to urban areas in Europe, which led to rapid urbanization processes that occasionally failed to adequately address the demands of the actual populace. Human existence oscillates between the search for and rejection of urban reality, as evidenced by the ensuing process of "counter-urbanization," which since the 1970s has witnessed a steady return to the countryside in many European cities (Girard et alii, 2003). One of the distinct features of the current Anthropocene is the contrast between the nature and the city, two qualities that do not coexist harmoniously. The contrast between the city and environment, which do not appear to be on equal footing—the former gives its residents amenities and services while unavoidably eating up space from the latter—is one of the most distinguishing characteristics of the current

Figure 26. High Line. One of the most iconic urban renaturation projects, the New York High Line recovers and enhances old train rails.

Anthropocene. Rethinking the contentious interaction between the built and natural environments is importanas a result of this occurrence, which divides, impairs, or disrupts ecosystems' regulatory processes (Neonato, Tomaselli, and Colaninno, 2019).

Recently, there has been an increased focus on the integration of natural processes with the urban environment in the design of public spaces and infrastructures (Figure 26). This has resulted in the promotion of a regeneration that is based on the activation of new social and environmental functions that are specific to the city (Perrone and Russo, 2019). Considerable thinking can be had from Scale Architecture's 2009 Infinity Forest Project installation in Sydney (Figure 27). The temporary installation, a verdant haven tucked away in an alleyway hemmed in by towering buildings and utilized as a laborer's shortcut, invites us to contemplate the potential of repurposing underutilized areas by reintroducing plant features that can have a positive impact on those who frequent the area. This strategy reinterprets the interaction between the built environment and nature by introducing a "gentle" infusion of greenery into the urban grid

Figure 27. The Infinity Forest Project. Recovered space for vegetation inclusion.

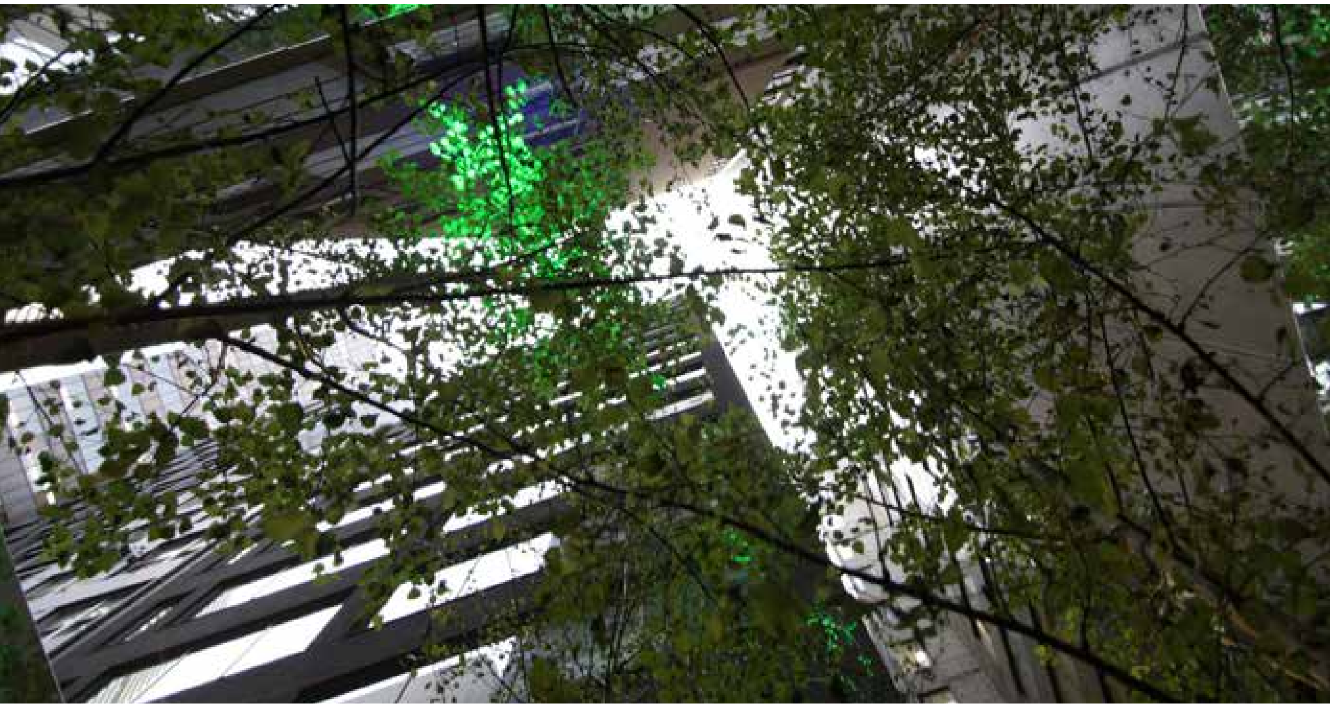


Figure 28. LUSH program. Systematic and highly technological integration of vegetation on the vertical development of the city of Singapore.

(Zaffi & D'Ostuni, 2020). This simulates the natural colonization processes that are typically impeded by human activity.
According to Marshall and Williams (2019), this "biophilic" approach to design suggests using vegetation as a tactic to "rewild" (Watson, 2021) and revive resilience systems in densely populated environments (Forman, 2014). An excellent example of how this strategy can be used to create an urban development plan where nature is used as a design tool

itself is the LUSH (Landscaping for Urban Spaces and High-rises) program, which the city of Singapore launched in 2009 (Figure 28). The initiative uses a variety of technologically advanced green solutions to take advantage of the expanding urban fabric to generate additional green areas. The suggested innovation promotes architectural concepts that increasingly bring the artificial and the natural closer by utilizing the vertical surfaces of skyscrapers as practical locations for the insertion of vegetal features (Figure 29) (Myers, 2018).
Particularly, in a flexible and non-intrusive manner, vertical greening solutions address the issues of the modern city by eliminating the shortage of space below ground and redefining the function and appearance of the building grid.

The development of these technologies and their use in contexts with diverse features have been gradually expanded due to advancements in both technology and form (Dunnet and Kingsbury, 2008). These vegetation systems create a "co-construction" link between the designer and the urban environment, enabling robust reactions (Tesoriere, 2019).

Figure 29. Bosco Verticale.
A real Manifesto of urban reforestation by Stefano Boeri Architetti.

2.3.2 Overview on real opportunities

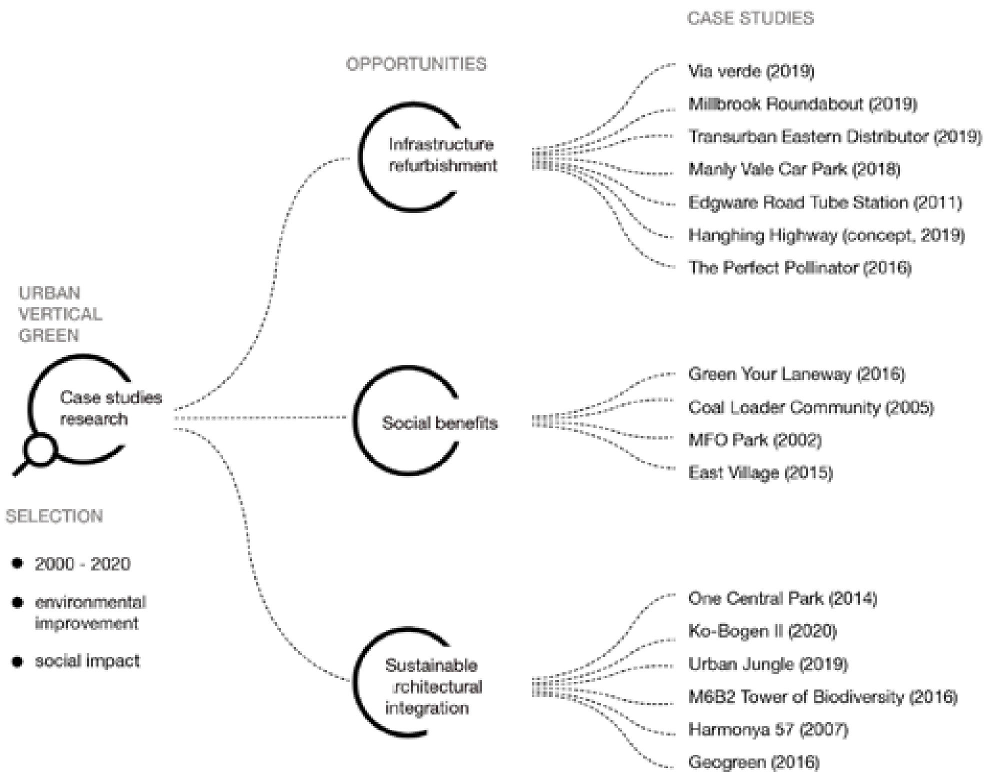
Through the exploration of sixteen case studies, sections 2.3.2 - 2.3.7 provide a modern perspective on the potential benefits of vertical greenery systems as multifunctional elements that can strenghten and enhance the urban environment, toward the resilient transition of cities.
In order to provide a wider framework for evaluating the impact of vertical greenery systems, the analysis is structured into three sections. The first presents examples of how this technology is employed as a "tool" at the infrastructure level to reactivate local regulatory processes in city. The second discusses on how using vertical greenery systems as a "strategy" for social cohesiveness and engagement, affecting society as a whole. In order to contrast environmental degradation, the final part examines how to harmoniously incorporate plants into building materials and design (Ratti and Belleri, 2020). This final part discusses the potential for enacting moral procedures on the land to create vertical greenery systems that make use of regional resources and foster communication between industry and academia.
To provide a thought that goes beyond a "verdolatric" perspective on the nature-built interaction (Bellini and Mocchi, 2017), From the perspective of social dynamics and environmental sustainability, the contribution emphasizes the links that vertical green systems build with the

land (Tesoriere, 2020). The information presented encourages contemplation on the possibilities of integrative design with vegetation in urban settings. According to Liu et al. (2007), successful implementation of this approach necessitates enhancing multidisciplinary communication between industry, research, ecology, and social sciences.

2.3.3 Methodology of the analysis

This essay presents a selection of sixteen projects significant in their action of reinterpretation of the surfaces of the urban fabric aimed at re-establishing a connection between the built environment and the network of environmental and social processes of the city (Table 2). The urban contexts analysed are of medium-large size, on a national and international scale,

Figure 30. Case studies. Structure of the selection and case studies of the analysis.



and in different climatic zones, in order to offer a wide-ranging view of the different declinations of vertical greening systems. The time frame under consideration includes the last twenty years, a period in which shared methodologies and design objectives have been found, leading to the experimentation of innovative solutions.

The projects are divided into three categories according to the opportunities offered from the point of view of environmental benefits and the activation of new spaces for sociality, showing an overcoming of the simple aesthetic function of green. The exploratory analysis considers the technical solutions adopted by the vertical greening systems to favour the re-functionalisation of the grey infrastructure, the creation of benefits from the point of view of the psycho-physical and social well-being of the local community and the sustainable integration

Table 2. Analysed case studies and data. Main information on the sixteen case studies analysed

Case study	Location	Designed / Constructed by	Year	Main aspects
Via verde	Mexico City	Verde Vertical	2019	traffic pollution removal
Millbrook Roundabout	London	Biotecture	2019	traffic pollution removal
Hanghing Highway (concept)	São Paulo	Triptyque Architecture, G. Blanche	2019	traffic pollution removal
Transurban Eastern Distributor	Sydney	Junglefy	2019	traffic pollution removal and monitoring
Manly Vale Car Park	Sydney	Junglefy	2018	air filtration
Edgware Road Tube Station	London	Biotecture	2011	traffic pollution removal in urban canyon
The Perfect Pollinator	London	Scotscape Landscaping Ltd. Bug Life, Wildlife World	2016	pollinators habitat improvement
Green Your Laneway	Melbourne	City of Melbourne	2016	heat island effect mitigation and social participation
Coal Loader Community	Waverton (Au)	City of Waverton	2005	vertical gardening and post-industrial site reuse
MFO Park	Zurich	Burckhardt+Partner, Raderschallpartner	2002	post-industrial site reuse for social activities
One Central Park	Sydney	Jean Nouvel Architects, P. Blanc	2014	systemic integration between building and vegetation
Urban Jungle	Prato	Stefano Boeri Architects, S. Mancuso	2019	urban regeneration and social participation
Ko-Bogen II	Düsseldorf	Ingenhoven Architects	2020	urban forestry
M6B2 Tower of Biodiversity	Paris	Edouard Francois	2016	building and vegetation hybridation
Harmonia 57	São Paulo	Triptyque Architecture	2007	vegetation and construction materials interaction
Geogreen	Portugal	C-MADE	2016	circular economy

between building and environment (Figure 30).

2.3.4 Environmental benefits for the development of green infrastructures

The role of vertical greenery systems in reducing pollution conditions through the physiological processes and morphological structures of vegetation is now a diffuse knowledge due to the increasing cooperation between scientific research and businesses in the testing and measurement of environmental benefits. Regarding implementation, some projects have shifted their focus from the building as the exclusive application site to the intricate network of urban infrastructures (Medl et al., 2015).

The Vía Verde project in Mexico City (Figure 31) involves covering more than a thousand pillars supporting the elevated Anillo Periférico highway with green

Figure 31. Via Verde, Mexico City.

Figure 32. Biotecture's Millbrook Roundabout infrastructure in Southampton (UK).

walls. Built in 2019 by architect Fernando Ortiz Monasterio of the company Verde Vertical, the project aims to "capture" and reduce the concentration of gaseous pollutants emitted by the intense vehicular traffic concentrated on one of the most heavily used motorway arteries in Latin America. The scale of the project led the designers to consider how the vertical green elements might affect the environment. The utilization of a layer of felt-based plant substrate created from recycled plastic was applied to balanc the structure's negative effects, even if the hydroponic system has a high water requirement.

In 2019, London-based Biotecture implemented a vertical greenery system at the Millbrook Roundabout infrastructure in Southampton (Figure 32). The primary objective of this project was to counteract high levels of atmospheric pollutants like carbon dioxide, ozone, sulphur, nitrogen dioxide, and particulate matter by harnessing the photosynthetic capabilities of specific plant species. Within ten hydroponic green walls, a total of seventeen different plant species were carefully selected, including *Euonymus*, *Convolvulus cneorum*, and *Acorus gramineus*, known for their leaf structures that effectively capture substantial quantities of PM10.

This innovative approach of incorporating vertical greenery into road infrastructure

Figure 33. Junglefy’s green wall along a section of the Transurban Easter Distributor highway

serves as an example in the case of the Minhocão viaduct conversion project in São Paulo, carried out in 2015 by the Franco-Brazilian firm Triptyque Architecture. Working in collaboration with landscape architect Guil Blanche, this project ingeniously integrates vertical and hanging greenery into the viaduct’s support structure. The selection of vegetation is of paramount importance here as well, with the use of Hedera helix, a plant species renowned for its ability to absorb PM10 atmospheric particulate matter (Sternberg et al., 2010).

Scientific research findings have laid the foundation for initiatives aimed at enhancing air quality control, exemplified by the interventions undertaken by the Australian company Junglefy (Pettit, Irga, and Torpy, 2020). This collaboration between Junglefy and academic research is evident in their vertical greening projects in Sydney, particularly along a section of the Transurban Easter Distributor highway in 2019 and the Manly Vale District interchange carpark in 2018. In the former case, green wall modules, comprising various plant species such as Westringia fruticosa, Nandina domestica, and Dichondra repens, have been installed along the highway guardrails (Figure 33) and equipped with air quality monitoring sensors. This setup facilitates data collection and the subsequent presentation of a compelling business case, promoting the advantages of employing green technology (Zupancic, Westmacott, and Bulthuis, 2015).

The second project involved the installation of a vertical greenery system across the entire facade of a building, serving as a natural buffer between the interior and exterior to enhance air quality. This system comprises twenty-seven plant species, encompassing both native and exotic varieties, including *Lomandra tanika, Viola hederacea*, and others like *Westringia fruticosa*, known for their appeal to pollinating insects.

Both instances exemplify responses to the challenge of maintenance, a pivotal phase in the management of vertical greenery. The system's adaptability to fit into space-constrained areas is one of the root causes of this maintenance complexity. In both cases, the systems can rotate 180 degrees, providing access to the vegetation without necessitating disassembly of

Figure 34. Biotecture's green walls installation at the Bakerloo Line station in Edgware Road, London (UK).

the support structure. The construction of the structural component demands finesse, with any alterations requiring the assurance of high durability, minimizing the need for frequent maintenance.

Furthermore, in 2011, Biotecture realised a green wall at the Bakerloo Line station in Edgware Road, London, (Figure 34) with the primary objective of mitigating the concentration of atmospheric particulate matter in a location marked by deficient green spaces. Vertical greenery systems are invaluable tools for reducing PM10 concentration in particularly vulnerable areas characterised by the 'urban canyon' configuration, which complicates the dispersion of gaseous pollutants (Abhijith et al., 2017). The project spans an area of 180 square meters and requires monthly maintenance to accommodate and nurture 14,000 plants from fifteen different species, all possessing leaf morphological characteristics well-suited for consistent PM10 capture.

These aforementioned projects underscore how the transition toward adopting green infrastructure can be achieved through the integration of plants elements that contribute to enhancing urban life quality, especially with regard to air quality.

Shifting the focus away from human-centric considerations, green walls also serve as a means to promote the biodiversity

Figure 35. Green Your Laneway project in Melbourne (Australia).

of flora and fauna by capitalizing on the urban environment's attributes. A case in point is the Perfect Pollinator modular system, created in 2016, designed by Scotscape Landscaping Ltd., Bug Life, and Wildlife World, in London. Through an accurate selection of floral species, this system creates a conducive habitat for pollinating insects. The widespread adoption of such green walls advocates for reinvigorating pollination processes, reinforcing the floral species biodiversity, and executing 'reconciliation' initiatives to reintegrate natural processes into the anthropogenic environment (Francis and Lorimer, 2011).

In the presented projects, vertical greenery systems are predominantly applied to mitgate localized anthropogenic pollution. Nevertheless, the substantial installation and maintenance costs remain a limiting factor, often constituting an investment with uncertain performance. Employing vegetation to alleviate pollutant concentrations in high-traffic areas (Defilippi Shinzato et al., 2019) is, in essence, a compensatory response that does not address the problem at its source. The selection of suitable vegetation, adapted to the specific climatic zone where the system is deployed, emerges as a pivotal element in effectively harnessing the environmental benefits of vertical greenery. Concurrently, it becomes imperative to deepen our understanding of how users perceive green technology to stimulate reflection and promote conscientious behavior.

2.3.5 Re-establishing a relationship with nature

The presence of greenery within the urban environment plays a crucial role in ensuring the physical and mental well-being of its residents (Dobson et al., 2021). Recent developments in the academic world have sparked growing interest in understanding the implications of the human-nature relationship on people's health, fostering a more comprehensive analysis of its social and relational consequences (Pérez-Urrestarazu et al., 2021). The following examples in this section explore the strategies employed to foster social cohesion in urban areas through vertical greening applications.

In this context, the Green Your Laneway Program, launched with the support of the City of Melbourne in 2016 (Figure 35), introduces a Regeneration Plan aimed at revitalizing a network of laneways that had been underutilized due to the oppressive urban heat island effect, making the spaces uncomfortable. Through collaborative planning involving the local community, this initiative envisions the introduction of greenery as a solution to enhance microclimatic conditions and thermal comfort. By implementing various forms of vertical greenery, ranging from green facades to hydroponic irrigation systems, these laneways have transformed into new hubs for attraction and social interaction. This ongoing program promotes activities and interventions that aim to establish a

local identity and engage the community in reclaiming unused spaces, fostering fresh relationships and dynamics (Manzini, 2018) through a 'bottom-up' perspective, leveraging the flexibility of vertical greening systems as an accessible tool for reinvigorating neglected areas.

An excellent example of this approach is the Coal Loader Cottage Community Garden, an urban association that revitalized a post-industrial site in Waverton, Australia. In 2007, they constructed a Multifunctional Centre dedicated to sustainability and housing a collective urban garden. The project, conceived in 2005, involved collaborative efforts between the local administration and the community during the planning and design phases. Various modular green walls were installed, facilitating experimentation with rainwater collection, phytodepuration systems, and vertical gardens for cultivating herbs, small vegetables, and fruit, all while avoiding the use of soil, which would have required reclamation in a post-industrial area (Figure 36).
The experience of the Coal Loader Community Garden is noteworthy as it offers the local community the opportunity to experiment with and design vertical greenery systems using cost-effective and recycled materials. This aspect is indispensable in the process of bringing citizens closer to

Figure 36. Coal Loader Community of Waverton (Australia).

and understanding the potential offered by various types of green walls. Despite generally positive perceptions of vertical green among users (Maron and Ramirez, 2020), there still exists a widespread belief in the management complexity and high maintenance costs. Oterh initiatives like the Openspace studio's project for the One Century Community space in Klong 3, Bangkok, in 2011, and the work of Akinwolemiwa et al. (2018) underscore the possibility of bringing the local community closer to the opportunities offered by vertical greening systems through a 'community-driven' approach.

Vertical greenery is also frequently viewed as a tool for regenerating industrial heritage, returning these spaces to the public. The MFO Park in Zurich, a project by Burckhardt+Partner and Raderschallpartner in 2002 (Figure 37), involved the revitalization of the galvanized steel structural framework within the former Maschinenfabrik Oerlikon, a historic manufacturer of machinery, weapons, and electric locomotives. As part of a park system created for the new residential center in the area, the project cloaked the entire structure with 1,200 different types of climbing plants, redefining the Pavilion's aesthetic appeal and the spatial perception. The vegeteted

Figure 37. MFO Park in Zurich (Switzerland).

structure serves as a social focal point welcoming residents and visitors daily and hosting cultural and recreative events.

These examples highlight how the integration of greenery into urban spaces not only enhances the physical environment but also fosters community engagement and social cohesion. In order to reap positive social benefits in the long term, it is important to design not only the structures of the systems, but also the forms of involvement and empowerment of users, envisaging a coexisting scenario between people and new urban greening.

2.3.6 Integration between greenery and building

In order to link the constructed environment to the teritory, the union of buildings an vegetation also serves as a method of overcoming the obvious division between urban and natural surroundings. A definition of architecture that can be interpreted as "man-made nature" is the particularity of the outcomes of this process, which is the concretization of a formal and functional hybridization (Ricci, 2020).
One Central Park, a skyscraper constructed in Sydney in 2014 by Jean Nouvel Architects

Figure 38 . One Central park in Sydney (Australia).

Figure 39. Kobogen II by Ingenhoven Architects in Düsseldorf (Germany).

and French botanist Patrick Blanc, is a component of a Regeneration plan that calls for transforming the post-industrial site into a residential neighborhood in the heart of the city. The unique aspect of the idea is how well the park's natural greenery is integrated into the base of the building complex and is artificially continued along the two flat blocks using green walls (Figure 38). While maintaining adequate solar radiation throughout the winter, the sizable area covered by flora helps to lower the energy consumption of the air conditioning system. A system for cleaning rainwater and gray water has also been installed in the building complex. This system is utilized to irrigate the hanging and vertical green areas, which creates a cycle in the resource usage. According to Wines (2008), the incorporation of the vegetative aspect during the design process turns the technical green into a useful component for the building's overall sustainability.

Referring to the Green Over the Grey concept, promoted by Emilio Ambasz (2016), vertical greenery is conceived as a partner for the creation of 'urban forests' superimposed on the buildings themselves. From this perspective, the Urban Jungle regeneration project in Prato begins to take shape in 2019. Stefano Boeri Architects and botanist Stefano Mancuso

Figure 40. M6B2 Tower of Biodiversity in Paris (France).

collaborate in an integrative manner on this project. The project's creative aspect lies in its extensive use of hanging and vertical greenery to include vegetation on every surface of the buildings envelopes. The redevelopment of the spaces also includes the activation of local participation dynamics and ecological education initiatives, as necessary tools to trigger a transition towards more sustainable forms of living. Both inside and outside the structure, the use of vegetation contributes to the enhancement of environmental quality. The Air Factory, a glassed-in

Figure 41. M6B2 steel cables structure.

bio-filtration system that harnesses the vegetation's phyto-purification processes to deliver clean air back into the structure, will be placed into an industrial building that is to be transformed into a shopping center.

The Kö-Bogen II building in Düsseldorf, created by Ingenhoven Architects in 2017 with the intention of supplying pure air to the city center, likewise makes extensive use of green façade (Figure 39). This project hybrid outcome, which alternates between an urban park and a building, become strong landmark of the urban space, referring to Land Art. *Carpinus betulus* hedges, an autochthonous plant that was specially selected for its high CO2 absorption capacities, covered the whole building envelope (Scharenbroch, 2011).

The process of hybridisation between the plant component and the building can also lead to the establishment of new relationships between the built project and the plant ecosystem. This is demonstrated by the M6B2 Tower of Biodiversity (Figure 40) residential complex in Paris, which was created in 2016 by architect Edouard Francois. The building is a manifesto to highlight the significance of biodiversity in urban settings. In fact, the building itself becomes a tool for sowing seeds thanks to the action of the wind, which disperses the seeds produced by the cultivated plant species in the surroundings. The building is covered by a network of steel cables on which climbing plants grow (Figure 41). Climbing species must develop slowly over an extended period of time to obtain enough envelope coverage. Because of this, the benefits take time to materialize, but this also introduces another innovative element: the contrast between the natural and urban times.

Going beyond the conventional approach of adding an external vegetated layer to a

building's facade, Triptyque Architecture introduced a novel concept in Harmonia 57, São Paulo, back in 2008. They seamlessly integrated vegetation with the building material, eliminating the need for a separate support structure for the plants. The walls of the building are constructed from organic cement, a porous and permeable building material with the capacity to retain water and moisture. These walls incorporate openings specifically designed to accommodate the growth of vegetation (Figure 42).
The selection of plant species was based on factors such as their growth rate, shade tolerance, and their ability to attach and thrive on the wall surface, thus creating a suitable substrate for other plants to flourish. This architectural innovation redefines the concept of vertical greenery systems and introduce to further experiments aimed at developing new alternative materials that can support the symbiotic growth of plant organisms (Riley et al., 2019).

This process of bringing together the built and natural materials (Corrado, 2020) fosters a design philosophy that consider the local territorial context as an opportunity to devise sustainable solutions. A relevant example of this approach is the Geogreen modular panel prototype, developed by C-MADE at the Universidade da Beira Interior in Portugal (Manso et al., 2018).

Figure 42. Harmonia 57 by Triptyque Architecture in São Paulo (Brasil).

Figure 43. Geogreen by C-MADE and the Universidade da Beira from Manso et al. (2018).

This innovative system reuse waste and by-products sourced from the local industrial supply chain. By reclaiming and processing materials like quarry sludge, waste from the production of expanded cork panels, and discarded materials from the glass industry, a sustainable support system for vegetation is created, obviating the need for traditional metal and plastic components (Figure 43).

It's worth noting that the experimental nature of the production process currently involves relatively high energy consumption, although this can be mitigated by establishing a small-scale production line. Nevertheless, the reuse of waste materials from other production processes can trigger circular mechanisms with positive economic outcomes for the local community. This sustainable design approach aligns with practices widely adopted across various sectors but is still in its initial stage concerning green technology. This suggests fascinating untapped research and development opportunities.

The cases presented in this section represent part of an emerging approach to the design of vertical greenery systems. Although the employed technologies and procedures are expensive and provide difficulties in controlling the plants component, they provide worth and novel opportunities for exploration. These obstacles may prevent widespread acceptance for the time being, but they do open the door for pivotal and fascinating developments in the field.

2.3.7 Innovating the practice

The cases under examination demonstrate a growing recognition in design practices of the 'performative' role of vegetation as an ornament capable of ameliorating critical urban conditions.

Despite the ongoing challenges associated with the installation and maintenance costs of vertical greenery systems, it is evident that the research for innovation may drastically overcome these issues. With broader adoption of such strategies, it can be anticipated a reduction in production and management costs, while simultaneously increasing the overall advantages.

Collaborative efforts between local administrations and the research community indicate a burgeoning interest in seeking solutions to mitigate the environmental costs - and therefore economic costs - of materials, systems, and processes.

Furthermore, the behavioral response to vertical greenery systems as a "technological greenery" is a relatively underexplored aspect and presents intriguing implications for co-design practices and activation of civic engagement of individuals. Leveraging vertical greenery to foster social cohesion and promote urban ecological principles can play a pivotal role in advancing broader and more systematic endeavors for cities to transition towards resilience.

While this analysis offers qualitative insights into the potential of vertical greenery system, incorporating quantitative data can enhance the environmental, economic, and social sustainability of vertical greening systems, leading to the development of structural components that are more intricately linked to the local context. Additionally, there exists an opportunity to leverage new resources within the framework of a circular economy, such as repurposing pruning residues to create organic substrates. It is indeed noteworthy to explore the active involvement of local communities in the management and maintenance of vertical greening systems, fostering circular processes for the reuse of plant waste (as emphasized by Malaguti de Sousa, 2019).

The diverse manifestations of vertical greenery systems showcased here suggest that this technology can effectively realize the holistic concept of 'urbanature' (as outlined by Yudina, 2019). They provided that its implementation is underpinned by interdisciplinary collaboration between the realms of research, design, citizens and local administrations.

Chapter 3

Sustainability of livig walls

Investigating new opportunities
for growing media

Synthesis of the chapter

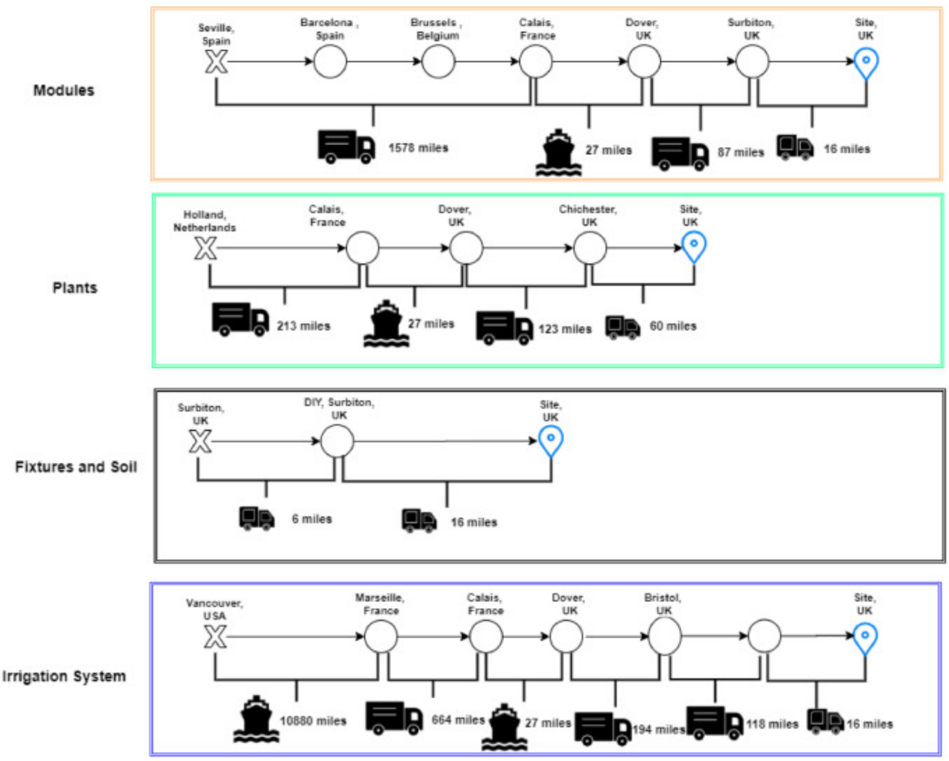
An empirical investigation was undertaken to assess the efficacy of six distinct alternative growing media, composed of locally-sourced waste and by-products, in supporting the growth of three different plant species. Based on the findings of this experiment, an evaluation of the suitability and sustainability of the growing media was conducted, considering their effectiveness in facilitating plant growth and three specific criteria related to the technical and ecological attributes of growing media: lightweight quality, water requirements, and volume stability. Furthermore, this research represents an initial step towards shaping a strategy for the sustainable design of vertical greenery systems, employing a design-by-components approach starting from the growing medium and subsequently defines other essential components.
This research broadens the research of growing media in vertical greening design and deepens the knowledge about: (1) the inclusion of environmental considerations as influential factors for growing media selection and (2) the exploration of alternative growing media specifically designed for vertical greenery systems. Consequently, this research lays the groundwork for establishing a methodology by which the sustainability and performance of alternative growing media for vertical greening can be systematically evaluated and compared.

The chapter exposes the author's reserach partly presented in Molari et al. (2024), published in the Journal of Cleaner Production.

3.1 Investigating the system sustainability

Urban greening emerges as a pivotal strategy with the potential to significantly enhance the livability of densely populated cities (Musa et al., 2022) and is today more and more frequently embraced as a means to address current pressing issues through nature-inspired approaches (Dorst et al., 2019). As discussed in the previous chapter, within the realm of urban greening, vertical greenery systems play a crucial role in transforming crowded urban environments into more sustainable and green spaces (Douglas et al., 2021). Vertical greenery systems exemplify multifunctional nature-based solutions designed to "protect, sustainably manage, and restore natural and man-made ecosystems to effectively and adaptively address societal challenges while benefiting both people and nature" (IUCN, 2020). Nonetheless, there is a

Figure 44. Vertical greenery systems life cycle. oundaries of vertical greenery systems life cyle from Salah and Romanova (2021).



noticeable absence of specific guidelines for the sustainable design and production of vertical greenery systems, particularly in terms of reducing their environmental impact.

In fact, scientific research has primarily focused on evaluating the environmental benefits, notably thermal performance, offered by vertical greenery systems within the built environment (Chàfer et al., 2021a).

A comprehensive review by Nugroho (2020) underscores the need for vertical greenery systems to evolve into more sustainable solutions by using materials with reduced embodied energy and CO2 emissions. This calls for the exploration of natural or recycled materials as potential innovative solutions.

In recent years, some academic studies have ventured into analyzing the environmental impacts of vertical greenery systems, assessing their sustainability for the first time (Figure 44). Several studies have adopted the Life Cycle Assessment (LCA) method to pinpoint the impact hotspots associated with various vertical greenery systems typologies and components. The pioneering study applying LCA to vertical greenery systems was conducted by Ottelé et al. (2013), which compared the environmental burdens of five distinct vertical greenery systems typologies. The findings emphasized the significant environmental impact of the materials used in constructing the components of any system. The study underscored the necessity of employing sustainable materials in vertical greenery systems to advance a sustainable design approach. Subsequently, both this study and the work of Manso et al. (2018) revealed that the support system had the most substantial environmental burden due to the resource-intensive supply chain of stainless steel. Following works applying LCA on vertical greenery systems have consistently highlighted the strong influence of the structural components on the life cycle of the entire system (Cortês et al., 2021; Salah & Romanova, 2021; Serra et al., 2017). In line with these results, Pan and Chu (2016) recommended a reduction in the quantity of material used in the structural components to significantly minimize the environmental impacts of vertical greenery systems. Recent years have seen a surge in material research and optimization for vertical greenery systems, resulting in innovative solutions such as Manso et al. (2018) proposal for a modular vertical greenery systems composed of scraps from cork and glass production, and Cortês et al. (2021) development and testing of a modular living wall using expanded cork agglomerate.

Nevertheless, it was only recently that LCA studies began to emphasize the pivotal role of growing media in accounting for vertical greenery systems environmental impacts. Oquendo-Di Cosola et al. (2020) and Mannan and Al-Ghamdi (2022) have affirmed in their work the significance of considering environmental impacts when selecting growing media materials, advocating for the use of organic growing media as a fundamental aspect of sustainable vertical greenery systems design. Notably, Chàfer et al. (2021a), in their comparative LCA between different vertical greenery systems typologies, recommended the application of sustainable strategies for growing media (e.g., recycled growing media) to significantly reduce the overall environmental impacts of the entire vertical greenery system. Reyhani et al. (2022) have underscored the substantial influence of some of the most commonly used artificial and inorganic growing media on the environmental assessment of vertical greenery systems. Their LCA-based work serves as a guiding tool for designing sustainable vertical greenery systems and suggests replacing impactful artificial growing media with more sustainable organic alternatives. Nevertheless, as Chàfer et al. (2021b) have highlighted, there remains a substantial research gap in the exploration of materials for vertical greenery systems , particularly regarding sustainable growing media. Although a few notable studies have undertaken sustainable growing media experimentation (Parada et al., 2021; Manríquez-Altamirano et al., 2020; Manríquez-Altamirano et al., 2021), the emphasis on the aware design, scientific evaluation, and production of bioresource-based growing media represents a pivotal strategy for sustainable urban greening projects. In their review, Koviessen et al. (2023) strongly advocates the urgency of finding alternative growing media through the circular use of local by-products and waste, to be applied in specific nature-based solutions, and how this strategy can accelerate the green transition of contemporary cities.

As asserted by Toboso-Chavero et al. (2021), in addition to chemical, physical, and biological properties, the environmental sustainability of growing media is now gaining importance in the selection process. Vandecasteele et al. (2023) argue that the development of new blends using renewable resources is the next frontier in advancing the sustainability of soilless horticulture. Some studies have underscored the use of organic materials as components of alternative growing media, including composts, bark, wood residues, and coconut coir (Barrett et al., 2016; Gruda, 2019). These organic materials are often combined with inorganic ones such as perlite, vermiculite, calcined and expanded clay, as highlighted by Sabatino (2020).

Notably, circular economy principles have been applied to create sustainable growing media derived from industrial by-products or from agricultural, industrial, and urban organic waste, as demonstrated by Raviv (2013). However, it is important to note that De Lucia et al. (2021) and Rivas-Sánchez et al. (2017) are the only two studies that have experimented with an agricultural by-product, such as rice husk, as a sustainable growing medium for vertical greenery systems .

3.1.1 Exploration of local opportunities

In alignment with the principles of circular economy and sustainable design, the present section present the research

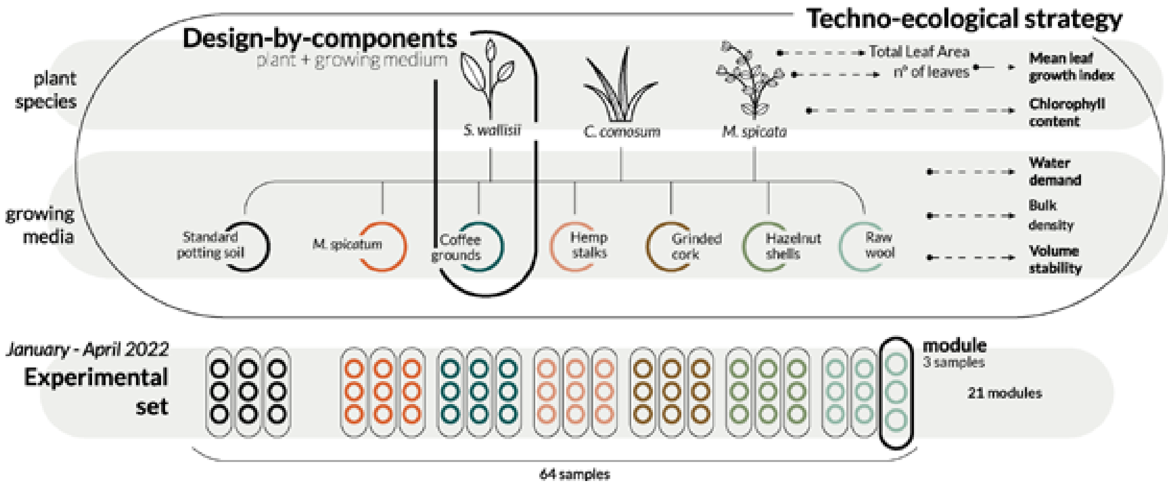


Figure 45. Methodological framework. Techno-ecological framework structured and followed in the study.

embarks on an experimental campaign involving various bioresource-based growing media intended for application in vertical greenery systems. These growing media are derived from organic waste and by-products sourced from the Piedmont Region (Italy). As demonstrated by Koley (2021), the innovative utilization of regional bio-resources stands as a strategy that carries the potential for numerous favorable outcomes within a locality. It facilitates the efficient management and reduction of resources, whether they pose environmental or health risks, while simultaneously fostering the establishment of novel short supply chain growing media. In alignment with the findings of Taupedi and Ultra Jr. (2022), implementing such a strategy necessitates conducting laboratory experiments to explore the properties of these bioresources, thereby enabling the development of competitive, eco-friendly substitutes for traditional, unsustainable soils.

Notably, one of the primary challenges of this research lies in the absence of established protocols for evaluating the sustainability of growing media. As a result, evaluation criteria for sustainable vertical greenery systems growing media have been established. To this end, a multi-criteria matrix, following the work of Alexander & Bragg (2014), has been developed to evaluate and compare the sustainability of the alternative growing media under examination. From a sustainable design perspective, three core functional requirements for vertical greenery systems growing media - namely, lightweight, durability, and low water demand - serve as the key evaluation criteria for assessing growing media sustainability.

An empirical study was developed to gauge the effectiveness of six distinct alternative growing substrates, meticulously crafted from locally sourced waste materials and by-products. These substrates were evaluated for their capacity to nurture the growth of three distinct plant species. Drawing upon the findings of this empirical investigation, an in-depth assessment of the sustainability of these growing substrates was carried out. This evaluation encompassed an analysis of their proficiency in fostering plant growth and took into account three distinct criteria pertinent to the technical and ecological attributes of the growing substrates: their lightweight characteristics, water requirements, and ability to maintain volume stability.

This approach (Figure 45) embraces a design-by-components methodology, starting with the design of the most appropriate growing medium, thereby laying the foundation for defining the oterg components.

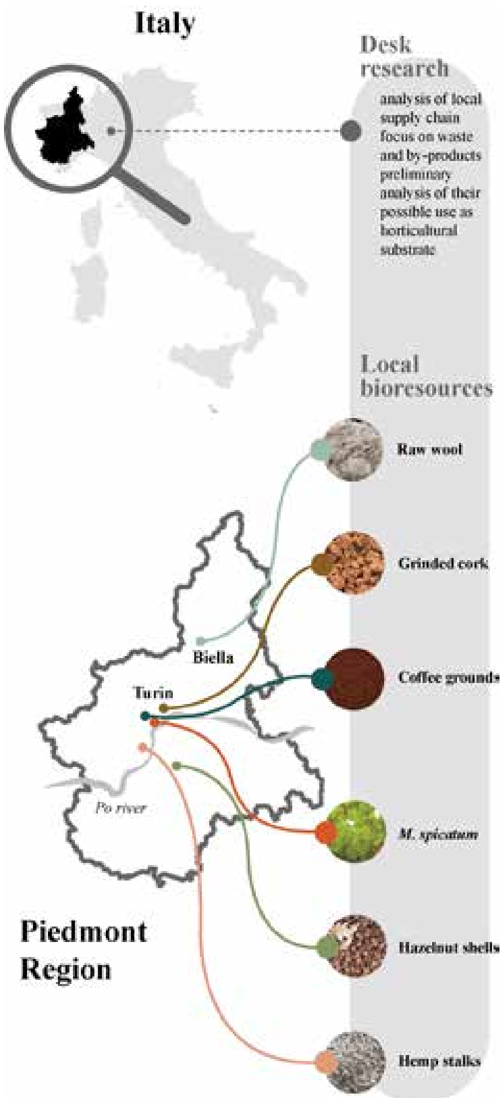


Figure 46. Desk research. Analysis of the local opportunities from bioresources re-use.

3.1.2 Local bio-resources selection

A preliminary desk research on the main by-products and waste of the Piedmont Region has been conducted to identify potential materials for alternative growing media (Figure 46). The economic framework of the region is predominantly characterized by agriculture, viticulture, rice cultivation, animal husbandry, automotive, textile, and food industries, in addition to financial and tourism sectors (Regione Piemonte, 2023). Following the principles of a circular bioeconomy (Brandão et al., 2021), six waste and by-products originating from local supply chains and urban streams were identified (Figure 47). The primary objective within this framework is to minimize the reliance on raw materials by utilizing waste and by-products as inputs for potential local production of growing substrates intended for vertical greenery systems (Scarpellini, 2022).

Moreover, the selection of local waste and by-products was guided by two fundamental factors: (1) their abundance and (2) their historical significance within the region. The valorization of abundant bio-resources that hold cultural importance locally (Padilla-Rivera et al., 2020) within a novel production system can foster environmentally, socially, and economically sustainable innovation (Donner et al., 2022). As elucidated by Hang (2022), capitalizing on context-specific opportunities and economies is generally a successful strategy for advancing a green economy, and its theoretical framework can be applied across various geographical contexts.
During this desk research, regional reports and national databases were consulted to assess the quantities of local by-products and waste, while scientific literature was examined to establish their potential suitability as growing substrates.

Among the identified materials, ground hemp stalks and hazelnut shells were chosen as promising by-products, both stemming from local cultivation and manufacturing.
Hemp cultivation in Piedmont has been historically renowned for its high quality since the days of the Roman Empire (Regione Piemonte, n.d.). While hemp cultivation currently represents only a modest share of the agricultural sector in the Piedmont Region, accounting for 7.4% of the national production (ISTAT, 2023a), innovative approaches within its supply chain have the potential to support diversification in the farming system, stimulate the creation of new local enterprises, and revitalize the market for this crop (Aluigi & Viganò, 2016).

Within hemp farming, two primary by-products are obtained: hemp fiber and hemp stalks. Hemp fiber finds its main application within the textile industry and has been previously explored in studies as an alternative growing medium, albeit with limited success (Dannehl et al., 2015; Clarke, 2010). In contrast, hemp stalks, the woody component of the plant, are

Figure 47. Local bioresources. The six selected bioresources have different nature as by-poduct or waste

Miriophyllum spicatum
municipal waste

Hazelnut shells
agricoltural by-product

(used) Cork stoppers
domestic waste

primarily used in the construction sector as a sound-absorbent material (Cavallaro, 2015). Several studies (Woznicki et al., 2021; Escobar-Avello et al., 2023) have demonstrated positive results using growing substrates based on wood fibers, which are characterized by high total porosity and air-holding capacity (Maher et al., 2008). Consequently, this study sought to evaluate hemp stalks as an

Hemp stalks
agricoltural by-product

Coffee grounds
domestic waste

Raw sheep wool
breeding waste

abundant and promising by-product with local significance.

Similarly, Piedmont stands out as the most prominent Italian region for hazelnut cultivation and processing, contributing to 28.5% of the total Italian hazelnut production (ISTAT, 2023b). Hazelnut shells, in terms of weight and volume, constitute the most substantial by-product generated during hazelnut processing. Conventionally, they find use as a heating source (Battistoni et al., 2020). Notably, hazelnut shells possess a substantial lignin content (Gordobil et al., 2020), a characteristic that, as demonstrated by research conducted by Dede and Ozdemir (2018), contributes to the physical stability of the substrate. While studies by Puliga et al. (2022) have explored the utilization of hazelnut shells as fundamental components of substrates for cultivating edible and medicinal mushrooms, investigations into their application within the floricultural and vertical greening domains remain limited. Nonetheless, according to reports by Barrett et al. (2016), the trend of utilizing nut shells as growing substrates has been on a steady rise. Consequently, the present research recognizes hazelnut shells as a promising prospect.

On the other hand, raw sheep wool, cork stoppers, coffee grounds, and fronds of *M. spicatum* were chosen as waste materials displaying potential for alternative growing substrates.

Raw sheep wool, sourced from Piedmontese flocks, was procured through a local wool consortium within the Piedmontese Textile District, a well-regarded symbol of the Made in Italy brand. Nonetheless, compared to international textile market standards, wool from Piedmontese flocks is considered of lower quality. In many instances, local breeders are left with no suitable options within the textile supply chain and consequently resort to discarding their raw wool as waste. In 2019 alone, the Piedmont Region registered 106,670 sheep breedings, which ultimately led to the disposal of nearly 160 tons of wool (Quaglia, 2023). Hence, the valorization of local sheep wool represents a promising challenge that addresses economic and social facets (Rajabinejad et al., 2019). As noted by Gabryś & Fryczkowska (2022), multiple studies have examined the use of treated and purified wool as growing substrates for plants. Furthermore, the utilization of raw sheep wool can significantly reduce the energy and resource consumption required for the wool cleaning process, thereby lowering the environmental impacts associated with the preparation of this alternative growing medium. Moreover, untreated sheep wool retains lanolin, a potassium-rich substance that can be employed as a plant fertilizer (Ikoyi et al., 2020; Cavalcante et al., 2020).

Piedmont holds a prominent position in Italy's wine production landscape, spanning from grape cultivation to sales (ISTAT, 2023c). The region boasts a widespread presence of wine shops and wine bars, particularly in its larger urban hubs (Regione Piemonte, 2021). However, in this context, cork stoppers are frequently discarded as waste rather than being recognized as a valuable resource for new supply chains. The cork material presents a fascinating hygroscopic property that holds significant potential for vertical greening applications by contributing to the thermos-hygrometric balance (Contreras et al., 2022). Additionally, Martinez et al. (2013) achieved promising outcomes utilizing a thin layer composed of cork and rice husk as a growing substrate.

Likewise, coffee is an important food commodity linked to the historical development of the coffee-roasting sector in the Piedmont Region. At the consumption stage of the coffee life cycle, substantial quantities of spent coffee grounds are generated as food waste. Despite the numerous opportunities to repurpose these grounds as a valuable resource (Bomfim et al., 2022), no concrete plans have been established at the local level for alternative applications. Notably, promising outcomes have been achieved by Tombarkiewicz et al. (2022) in utilizing spent coffee grounds as a soil improver, which subsequently led to the consideration of this waste as a prospective resource for plant cultivation.

Finally, fronds of *M. spicatum* were chosen as a prospective resource due to their common disposal as special waste by the Municipality of Turin (Gruppo di Lavoro Specie Esotiche della Regione Piemonte, 2017). *M. spicatum* is an introduced aquatic weed that proliferates during the summer in the Po River due to the eutrophication of the freshwater ecosystem. This species is listed as an invasive introduced species of significant concern in Regulation (EU) 1143/2014, and its rapid eradication and environmental management are subject to stringent regulations involving mechanical removal (Arpa Piemonte, 2016). In this study, fronds of *M. spicatum* were manually collected from the banks of the urban stretch of the Po River in Turin.

Since the experimental work use local bio-resources, it has to be disclaimed that performances and results are necessarily dependant from the supplier and geographical context in which materials have been produced and recovered. For this reason it can be foreseen that the reproposition of the present protocol with the same kind of materials but in other geographical context will not return the same results obtained in the this work.

3.1.3
Plants growth and growing media quality

Nevertheless, the primary consideration in assessing the efficacy of a growing medium is its ability to support plant growth effectively. An alternative growing medium holds promise if it can ensure plant growth equal to or greater than that achieved with traditional media, as observed by Leiber-Sauheitl et al. (2021). Non-destructive methods for assessing plant growth are preferred over destructive ones, as they allow for the preservation of plants and repeated measurements during the experiment, as advocated by Hilty et al. (2021). Parameters such as leaf length and width, the number of leaves, plant or stem height, length, volume, and root density are typically measured to evaluate plant biomass growth, as reported by Caser et al. (2017) and Furbank and Tester (2011). Additionally, leaf length and width can be used to calculate the Total Leaf Area, and these parameters can define the growth rate, as illustrated by Charles et al. (2011). In some studies, chlorophyll content is measured using specific instruments that provide on-site information about plant health in a non-destructive manner, as indicated by Brown et al. (2022) and Gottardini et al. (2014).

3.2 The experiment: materials and methods

This research builds upon and enhances the experimental framework introduced by De Lucia et al. (2021) for the evaluation of an alternative growing medium based on bio-resources designed for VGS. The modified protocol devised in this study involved an expanded range of alternative growing media and assessed their efficacy based on environmental criteria derived from a comprehensive literature review.

The experimental procedure (Figure 48) encompasses two primary phases: (1) the preparation of experimental materials and setup (Sections 3.2), and (2) the execution of the experimental phase (Sections 3.3).

3.2.1 Materials preparation

This stage comprises several key steps: (i) blending the chosen bio-resources with potting soil to create the six alternative growing media; (ii) evaluating their phytotoxicity; (iii) examining their physical properties; (iv) assessing their

Figure 48. Expriment diagramm. Procedure followed for the experimet preparation and development.

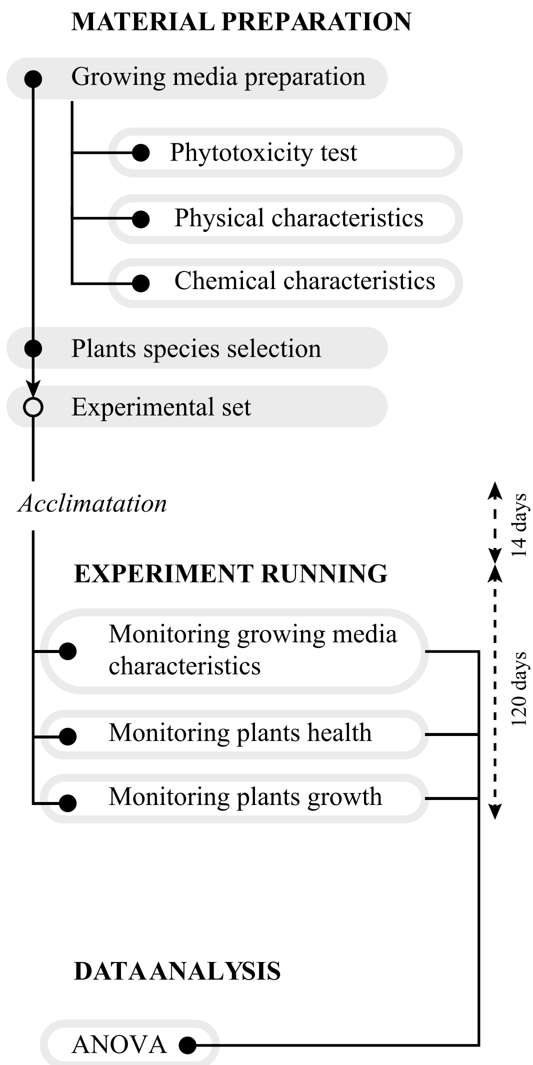


Figure 49. Alternative growing media. Each bioresources was mixed with standard potting soil in volume 50:50.

chemical characteristics; (v) selecting the plant species for the experiment; and (vi) preparing the experimental setup.

To ensure consistency and maintain an entirely organic composition for the alternative growing media, potting soil was chosen as a standard additive. While other less flexible inorganic materials like perlite and expanded clay are commonly employed in vertical greenery systems applications, the use of potting soil allows to highlight the impact of the integrated bio-resources within the growing media blends.

3.2.2 Growing media preparation

To create the six alternative growing media, each bioresource was combined with a standard potting soil designed for floricultural applications (COMPO SANA®). This potting soil is composed of neutral sphagnum peat, green composted soil improver, and a minor amount of mineral fertilizers. These alternative growing media contained a small quantity of fertilizers. A 50% volume ratio of each bioresource was manually mixed with 50% of potting soil to achieve uniform consistency (Figure 49). Volume was choosen as unit of measure being commonly used in growing media market. In this way, the use of material can be compared to the real necessity for the construction of a VGS. The reduction of the 50% of standard growing medium is meant as a strategy to decrease the demand of that resource, limiting the impacts of its suply chain and replacing it with locally produced material. Moreover, according to the bioeconomy principles that guided the conceptualisation of the work (Food and Agriculture Organization of the United Nations, 2018), the replacement with 50% of bio-resources was considered a substantial portion of material to improve the sustainability of a local production of growing medium. The application of the same ratio to all the local bio-resources is a way to compare the resulting weight of the alternative growing media. Infact, the present work takes into consideration the weight of the growing medium as functional requirement, thus ratio must be equal for all the materials.

Raw sheep wool, coffee grounds, and ground hemp stalks required no special pre-treatment. However, cork stoppers, hazelnut shells and *M. spicatum* needed preparation before mixing.
Hazelnut shells were shredded using an electric milling machine (‎YM221230879, AATAY) to achieve shell shreds measuring 0.5 - 1 cm in length. This step was essential to prevent water retention within the shell cavities after irrigation, which could lead to root rot.
Cork stoppers were ground using a standard blender equipped with stainless steel blades (CB-410, Horett) to obtain cork granules measuring 0.3 - 1 cm in length.
Fronds of *M. spicatum* underwent the most extensive pre-treatment process. After being collected from the Po River, the fronds were air-dried at room temperature (17±2 °C) for one week. They were then ground using a standard blender, resulting in a powdery material composed of particles ranging from 0.01 cm to 0.3 cm.

3.2.3 Phytoxicity of growing media

The phytotoxicity of the alternative growing media was assessed in accordance with the method outlined by Charles et al. (2011) to detect any detrimental effects of contaminants on seed germination, as described by Martignon (2009). This analysis is both cost-effective and straightforward to perform, delivering highly dependable results, as supported by the works of Bragança et al. (2018) and Guevara et al. (2019).
The phytotoxicity test involved triplicate samples of three plant species: *Eruca vesicaria ssp. Sativa, Nepeta cataria*, and *Lactuca sativa*. For each alternative growing medium (10 g), 100 ml of demineralized water was added, followed by hourly shaking for 12 hours. The resulting mixture was then filtered through a 45 μm filter paper to obtain an eluate. Subsequently, germination tests

were conducted using triplicate samples for each growing medium. In each sample, ten seeds were placed on a cotton filter within a Petri dish. Five milliliters of the eluate were added to the test samples, while the three control samples received 5 ml of demineralized water. These Petri dishes were incubated in darkness at a temperature of 25±1°C for a duration of 72 hours. Germinated seeds were identified based on the presence of shoots with a root length of at least 3 mm, as outlined by Margenat et al. (2017).

To deem the test acceptable, Seed Germination (SG) had to meet or exceed 80%, which was determined using the following formula (Margenat et al., 2017):

(formula 1)

SG% = (number of seeds germinated) / (number of total seeds) %

3.2.4 Physical characteristics of growing media

The measurement of Dry Bulk Density (D) for each growing medium was conducted in accordance with the procedure outlined by Rai et al. (2017). This parameter holds significant importance in the context of vertical greenery systems growing media, as it has a substantial impact on the overall weight of the system, which, in turn, influences the design of the anchoring system, as suggested by Dede et al. (2019). Using lighter growing media can potentially lead to a reduction in the weight of the structural system. Therefore, information pertaining to the bulk density of growing media is vital in the design of green walls, with the goal of minimizing weight and the demand for materials.

To determine D, a specific quantity of each of the seven growing media samples was placed in a graduated container, and the volume of 200 ml of material was collected. Subsequently, each growing media sample was weighed using an electronic balance, and the bulk density was calculated for each growing medium using the formula provided by Rai et al. (2017).

Total Porosity (TP) was measured for each growing medium based on the method established by Landis (1990). In this procedure, a graduated cylinder (2 liters) was initially filled with 1 liter of water, followed by the gradual addition of 1 liter of the dried growing medium. The porous volume of each growing medium was determined using the formulas specified by Landis (1990).

To assess Water Holding Capacity (WHC) for each growing medium, the Keen Raczkowski box method, as detailed by Govindasamy et al. (2022), was employed. This process yields a critical percentage value that indicates how efficiently the substrate retains water, a fundamental parameter in evaluating the suitability of growing media.

3.2.5
Chemical characteristics of growing media

To determine the pH and Electrical Conductivity (EC) of the alternative growing media, we followed the methodology outlined by Castro Garibay et al. (2019).
For pH determination, a specific quantity of the growing medium (400 ml) was mixed with distilled water (1000 ml) in a container, following a 1:2.5 concentration ratio. The resulting solution was allowed to stand for 30 minutes. Subsequently, the solution was distilled into a beaker through a funnel equipped with filter paper. A pH meter was then immersed in the distilled solution, and measurements were recorded. This procedure was carried out for each of the alternative growing media.
To measure EC for each growing medium, a petri dish (diameter = 8.5 cm; height = 1.5 cm) was filled with the prepared solution (consisting of distilled water and the growing medium). A digital conductometer was employed by placing the anode and cathode at the endpoints of the petri dish diameter and submerging them in the solution. The results of the EC measurements were duly recorded.

Figure 50. Experimental set. 21 pots (modules). For each plant species, one module has been prepared for each of the six alternative growing media and for the regular potting soil. Each module contains three plant samples.

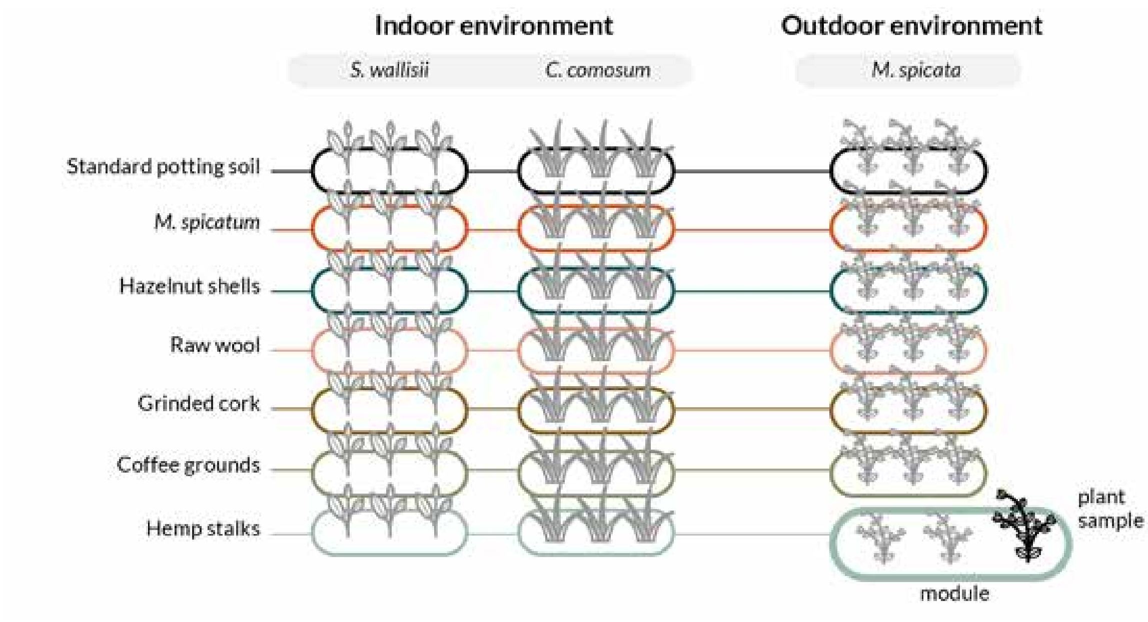


Figure 51. Plant species. *M. spicata*, *C. comosum* and *S. wallisii* were tested with the six alternative growing media.

Mentha spicata
Lamiaceae

Chlorophytum comosum
Asparagaceae

Spathuphyllum wallisii
Araceae

3.2.6 Plant species selection

Three plant species (Figure 51), well-suited to thrive in diverse environmental conditions, were carefully chosen to evaluate the effectiveness of the alternative growing media. In particular, the study encompassed the inclusion of *C. comosum* and *S. wallisii* for indoor applications. The selection of these species was underpinned by their impressive adaptability to indoor settings, as well as their minimal maintenance demands, as reported by Kwon et al. (2021). These plants not only bring aesthetic value but also contribute to enhancing indoor air quality through their natural purification abilities. This combination of features makes *C. comosum* and *S. wallisii* align perfectly with the incorporation of greenery into interior spaces.

Similarly, the *M. spicata* was included in the study for its attributes for air purification. This plant species possesses a set of advantageous features, such as the presence of leaves and stalk wax, trichomes, distinct leaf morphology, and a textured surface with roughness. These characteristics have gained attention in previous studies for their potential in effectively capturing air pollutants, as thoroughly demonstrated by Vigevani et al. (2022). Furthermore, *M. spicata* as well is successfully used in vertical greenery systems applications (Dorais et al., 2020).

3.2.7 Preparation of the experimental set

To facilitate the experiment, three sample of each plant species were cultivated in separate pots, each measuring 40 cm in length, 14 cm in width, and 12 cm in height. These pots were filled with one of the six alternative growing media or, as a control test, standard potting soil. Each pot, regardless of its content, accommodated 3 liters of the growing medium. Consequently, a total of 21 pots were arranged, with each pot containing a distinct growing medium and three plants of the same species. (Figure 50) To ensure uniform watering conditions across various growing media with differing porosities, plant pot trays were employed. These trays collected any excess water, ensuring that each plant received the same quantity of water.

Among these pots, seven were allocated to *C. comosum* and seven to *S. wallisii*, and these pots were situated in a controlled indoor environment at a stable temperature of 17±2 °C. On the other hand, seven pots were designated for the cultivation of *M. spicata*, and these pots were placed in an outdoor setting. Plant acclimation was performed for 14 days in order to match the requirements of different plant species (Retkute et al., 2015). Throughout this acclimation phase, plant hydration was regulated based on substrate moisture levels and the prevailing environmental conditions. *C. comosum* and *S. wallisii* were watered with 300 ml of water per pot, while *M. spicata* received 500 ml, adhering to an average water quantity determined in accordance with prior studies by Gubb et al. (2018), Gabrys and Fryczkowska (2022), and De Lucia et al. (2021). In addition to regular watering, a liquid fertilizer formulated for ornamental plants, consisting of NPK 7-5-6 with essential micronutrients including boron, copper, iron, manganese, molybdenum, zinc, and potassium, was administered to all pots via fertigation. This entailed the mixing of 20 g of liquid fertilizer with 2 liters of water to provide essential nutrients to the plants throughout the duration of the experiment.

3.3 Experiment running

To empirically assess the effectiveness and sustainability of the six alternative growing media in comparison to the control test using potting soil, specific criteria were diligently measured throughout a 120-day evaluation period.
Criteria were chosen to provide a holistic understanding of the attributes of the growing media as well as the growth and health of the plants. Thus, criteria were thoughtfully categorized into two distinct groups:

Growing Media Characteristics - criteria related to the properties of the growing media, including humidity, water demand, and volume stability. These parameters were of crucialt importance in gauging the environmental sustainability of the growing media, providing valuable insights into water consumption and material durability, as advocated by Vinci and Rapa (2019).

Plant Growth and Health - criteria such as the number of leaves, Total Leaf Area, and chlorophyll content. These factors were fundamental for assessing the development and health of the plants. Specifically, the number of leaves and the Total Leaf Area were instrumental in quantifying the plants' overall growth, while chlorophyll content emerged as a dependable indicator of their health, in accordance with findings from Paturkar et al. (2022), Dominici et al. (2021), and Kakouei & Salehi (2013).
This evaluation allowed for a comprehensive understanding of the performance of alternative growing media'and their impact on the cultivated plants, guiding the assessment from both environmental sustainability and plant health perspectives.

3.3.1. Monitoring the growing media characteristics

The assessment of water demand emerged as a pivotal parameter, shedding light on the water utilization patterns of each growing medium. Over the course of the experiment, the cumulative watering quantities were recorded, providing valuable insights into the water consumption associated with each growing medium. In parallel, soil humidity levels were closely monitored to manage the irrigation frequency. A regular measurement of soil humidity in all 21 pots were performed using a manual hygrometer equipped with a 10-point scale (T10 Bodentester, BATOU), and readings were taken every three days.

Furthermore, the examination of volume stability played a pivotal role in assessing the structural integrity of each growing medium. A greater degree of stability in volume signifies reduced maintenance needs and minimizes the necessity for medium replacement. This, in turn, leads to a reduction in waste generation and economic outlays associated with specialized labor and disposal services. The evaluation of volume stability was executed by measuring the volume of each pot at the beginning and conclusion of the experiment, providing a comprehensive view of the durability of tested growing media.

3.3.2. Monitoring the plant health

Chlorophyll content (in µmol of chlorophyll per m2 of leaf) was assessed using the Apogee Mc-100 optical handheld meter. To capture a comprehensive view of chlorophyll levels, sampling was conducted twice a month, since the focus of the experiment was the response of plants in the long period, not at daily base (Padilla-Rivera et al., 2020). It's worth noting that chlorophyll content serves as a widely recognized indicator of plant health, with a decrease often signifying plant stress, as corroborated by Pavlovic et al. (2014) and Liang et al. (1997).

The Apogee Mc-100 meter, typically employed in agriculture, offers valuable insights into the health of crops. It delivers assessments of the stress levels induced by factors such as nutrient deficiencies, inadequate irrigation, and adverse climatic conditions (source: https://www.apogeeinstruments.com). The chlorophyll concentration meter is composed of two light-emitting diodes—one in the red region and the other in the near infrared—along with paired receptors. This handheld device is equipped with an LCD display, a keypad, and two ports: a USB port for data download to a PC and an RS-232 port for GPS use.

Designed for instantaneous, direct, and non-destructive determination of chlorophyll concentrations in leaves, the meter operates by measuring the ratio between the transmittances of two radiations. One radiation is from the red region, and the second is from the near-infrared region. The instrument internally calculates the chlorophyll concentration value, which is then displayed on the LCD screen.

For the present work, the process of measuring chlorophyll content involved randomly selecting three leaves from each plant and performing five consecutive measurements per leaf, ensuring the accuracy and reliability of the results.

Operationally, to record the chlorophyll concentration, the optical sensor was placed and pressed on a random spot on the selected leaf and moved for subsequent measurements on the same leaf in order to obtain an average of the random chlorophyll concentration measurements per leaf.

3.3.3. Monitoring the plants growth

The evaluation of plant growth was performed twice a month and involved the measurement of Total Leaf Area (TLA) using the non-destructive method initially proposed by Dominici et al. (2021). This method entails manual measurements of leaf length and width for each plant species, following the guidelines established by Zhang et al. (2018). Subsequently, the leaves were categorized into four distinct topos, or leaf models, based on their average surface area.
To calculate leaf surface area, an AutoCAD drawing sheet was employed. Within this tool, lengths and widths of each topos were meticulously reproduced using the [Polylines tool], resulting in enclosed polyline geometries necessary to define the leaf surface area through the AREA Command. The TLA was then determined by summing the surface areas of all the leaves composing a single plant and is expressed by the following formula:

(Formula 5)

TLA = (L1 x W1) + (L2 x W2) + (L3 x W3) …+ (Ln x Wn) (cm2)

L: leaf length
W: leaf width

Tracking the Monitoring the number of leaves provides insights into the changes in foliage density over time and offers valuable information regarding the quality of plant growth, as highlighted by Dobrescu et al. (2017).

Both the TLA and the number of leaves from the three plants within each pot (module) were utilized to establish a novel metric known as the Mean Leaf Growth Index (MLGI):

(formula 6)

MLGI = (TLAf / nlf) **-** (TLAi /nli) (cm2)

TLAi : initial total leaf area
TLAf : final total leaf area
nli : initial number of leaves
nlf : final number of leaves

Consequently, the MLGI provided insights into the progress of the plants within a vertical greenery system module.
When the MLGI registers a value higher than 0, it signifies that the plant growth exhibited a positive trend, with both the TLA and the number of leaves increasing. In contrast, if the MLGI equals 0, it indicates that the plants did not experience

any growth. However, when the MLGI falls below 0, it suggests a declining trend in plant growth. In instances where all three plants within a module perished during the monitoring period, the MLGI was deemed null.

3.4 Data analysis

A Two-way Analysis of Variance (ANOVA) was conducted to investigate the effects of the seven different growing media on two parameters: chlorophyll content and TLA. This statistical analysis served as a robust tool for scrutinizing the intricate interplay of various growing media and their direct impact on plant health and growth

3.4.1 Statistical analysis: ANOVA

Consequently, two separate analyses were conducted for each of the two dependent variables: TLA and chlorophyll content. Plant species and growing media were designated as the independent variables, with three levels for plant species (*C. comosum, S. wallisii and M. spicata*) and seven levels for growing media. For each analysis, two hypotheses were formulated:

Null Hypothesis (H01): No statistically significant differences exist in TLA among the various growing media and plant species.

Alternative Hypothesis (Ha1): Statistically significant differences are observed in TLA among the various growing media and plant species.

Table 3. Phytotoxicity test. Results of the phytotoxicity test for each alternative growing media and seed species.

Growing media	*Eruca vesicaria ssp. Sativa*	*Nepeta cataria*	*Lactuca sativa*
Hazelnut shells	90%	90%	100%
Grinded cork	100%	100%	90%
Hemp stalks	100%	90%	100%
M. spicatum	90%	90%	90%
Sheep wool	90%	90%	90%
Coffee gorunds	90%	90%	90%

Growing media	pH	EC (µS/cm)	TP (%)	WHC
Hazelnut shells	7	743	70%	45
Grinded cork	7	401	70%	52
Hemp stalks	6	1116	80%	70
M. spicatum	6	4080	50%	67
Sheep wool	7	1540	90%	70
Coffee gorunds	6	2340	50%	54
Potting soil	7	400	90%	85

Table 4. pH and Electrical Conductivity for each growing media, Table 3. Results of the Total Porosity and Water Holding Capacity for each growing media.

Null Hypothesis (H02): There are no statistically significant differences in chlorophyll content among the different growing media and plant species.

Alternative Hypothesis (Ha2): Statistically significant differences in chlorophyll content are present among the different growing media and plant species.

The data for TLA and chlorophyll content were organized into two separate Excel spreadsheets, with plant species represented as columns and growing media as rows. The two-way ANOVA analysis was conducted using Excel's "data analysis" tool:

Data > Data Analysis > Two-Way ANOVA with Replications

The analysis generated p-values for each factor and their interactions, allowing for the identification of significant variations in TLA and chlorophyll content based on the factors of growing media, plant species, and their interactions. Statistical significance was determined at a p-value less than 0.05.

3.5 Results: growing media performance and plants development

The outcomes encompassing the attributes of the growing media and the progress of the plants are detailed below. In order to present the findings with utmost clarity and coherence, this section delves into distinct aspects: (1) the evaluation of phytotoxicity, chemical and physical attributes of the growing media, (2) the sustainability considerations surrounding the growing media, (3) the comprehensive assessment of plant growth, and (4) an in-depth exploration of plant health.

3.5.1 Characteristics of growing media

The following tables provide a comprehensive overview of the results pertaining to phytotoxicity, chemical characteristics, and physical attributes of the growing media. Notably, all the alternative growing media demonstrated favorable results in terms of phytotoxicity, facilitating the germination of nearly 80% of the seeds (Table 3).

With respect to the pH values (Table 4) of the alternative growing media, they closely align with the pH value of the standard potting soil. Growing media based on hazelnut shells, ground cork, and sheep wool exhibit a neutral pH value identical to that of the potting soil. Conversely, those based on hemp stalks, *M. spicatum*, and coffee grounds possess a slightly acidic pH of 6. I

For what concerns EC (Table xx), ground cork-based growing media closely approximate the value of the potting soil, followed by hazelnut shells-based growing media. The remaining growing media exhibit significantly higher EC values, with coffee grounds and *M. spicatum*-based media exceeding the potting soil's EC by nearly five times.

While the TP (Table 4) falls below the potting soil's value, it maintains favorable levels, surpassing the 50% threshold recommended by Havis and Hamilton (1976) for hazelnut shells-based, ground cork-based, hemp stalks-based, and sheep wool-based growing media. In terms of WHC (Table xx), all the growing media meet the 40% threshold as established by Tjosvold (2019).

Nevertheless, only hazelnut shells-based growing media exhibit WHC values similar to that of potting soil, as all the other growing media boast WHC values in excess of 100.

3.5.2 Sustainability of growing media

Table 5 provides a concise summary of the key characteristics of the growing media under examination during the experiment. In the initial phase of the study, bulk density measurements revealed that all six alternative substrates exhibited lower weights compared to the standard potting soil, ranging from 0.04 g/cm3 to 0.48 g/cm3. Remarkably, growing media based on raw sheep wool displayed the lowest bulk density at 0.04 g/cm3. Hazelnut shells-based (0.48 g/cm3) and coffee grounds-based growing media (0.42 g/cm3) featured bulk density figures similar to that of potting soil, while the remaining three alternative growing media weighed half as much as potting soil (M. spicatum-

	Bulk density (g/cm^3)	Volume stability			Water demand (ml)		
		C. comosum	*S. wallisii*	*M. spicata*	*C. comosum*	*S. wallisii*	*M. spicata*
Raw sheep wool	0,04	40%	40%	30%	1500	1500	2000
M. spicatum	0,25	50%	50%	45%	1800	1800	1500
Hemp canapule	0,29	85%	85%	75%	3000	3000	3500
Grinded cork	0,3	90%	90%	85%	2400	2400	2000
Coffee grounds	0,42	70%	70%	65%	1800	1800	2000
Hazelnut shells	0,48	85%	85%	80%	3600	3600	3500
Standard potting soil	0,52	70%	70%	65%	3300	3300	4000

Table 5. Growing media sustainability. The table shows the bulk density of growing media tested and volume stability and water demand for each combination of plant species and growing media.

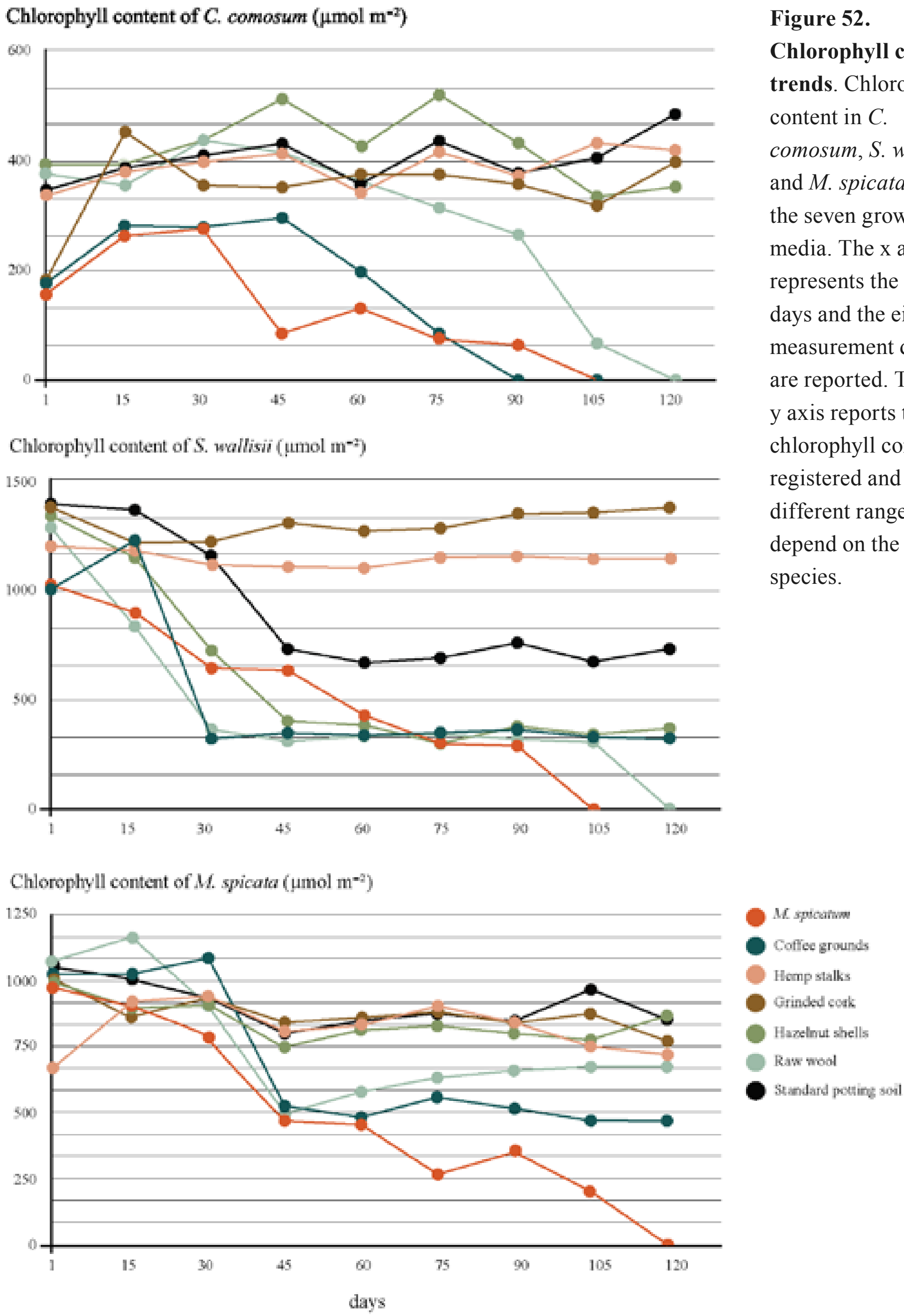


Figure 52. Chlorophyll content trends. Chlorophyll content in *C. comosum*, *S. wallisii* and *M. spicata* with the seven growing media. The x axis represents the days and the eight measurement days are reported. The y axis reports the chlorophyll content registered and the different ranges depend on the plant species.

based = 0.25 g/cm3; ground cork-based = 0.30 g/cm3; ground hemp stalks = 0.29 g/cm3).
The findings further illuminated that the volume stability of the growing media was contingent on their positioning, whether indoors or outdoors. In a general trend, raw sheep wool-based and *M. spicatum*-based growing media exhibited lower volume stability (ranging from 30% to 50%) than the other growing media (ranging from 65% to 70%). The coffee grounds-based growing medium demonstrated the same volume stability as potting soil, while hemp stalks-based, ground cork-based, and hazelnut shell-based growing media boasted the highest volume stability, ranging from 75% to 90%.

Both raw sheep wool-based and *M. spicatum*-based growing media necessitated a reduced water supply (ranging from 1500 to 2000 ml per module) compared to the other alternative substrates. Nevertheless, all the alternative growing media showcased decreased water demand in comparison to potting soil, with requirements ranging from 3300 to 4000 ml per module.

3.5.3 Plants health in response to different growing media

The seven alternative growing media yielded varying chlorophyll content results in *C. comosum, S. wallisii* and *M. spicata*, as illustrated in Figures 52.
A two-way ANOVA analysis underscored the consistent impact of the seven growing media on chlorophyll content across all three plant species. Variance was found to be significant within plant species, growing media, and between the two ($\alpha < 0.5$).

To delve into specific outcomes, in the case of *C. comosum*, it maintained a stable trend of chlorophyll content when grown in hazelnut shells-based, hemp stalks-based, and ground cork-based growing media. However, *C. comosum* cultivated in raw sheep wool-based growing media exhibited a substantial reduction in chlorophyll content from the 30th day of the experiment. Similarly, both coffee grounds-based and *M. spicatum*-based growing media led to a decrease in chlorophyll content starting from the 45th day.

In regards to *S. wallisii*, this plant species exhibited a decreasing trend in chlorophyll content for nearly all growing media, including the control potting soil. Exceptions to this trend were observed with hemp stalks-based and ground cork-based growing media, which maintained stable chlorophyll content patterns in S. wallisii.

As for *M. spicata*, hazelnut shells-based, ground cork-based, and hemp stalks-based growing media consistently produced stable chlorophyll content throughout the entire duration of the experiment. In contrast, *M. spicatum* grown in its own-

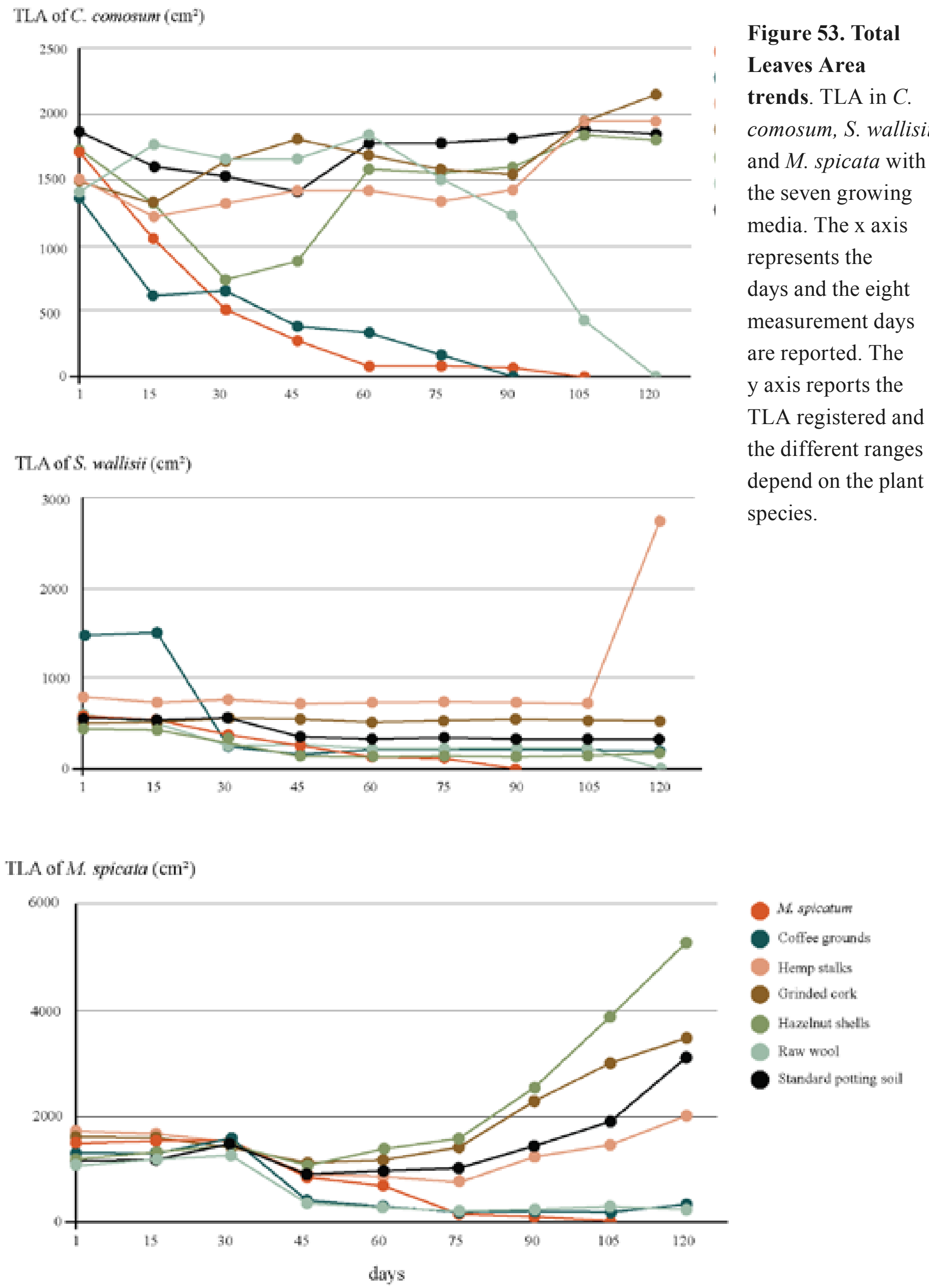


Figure 53. Total Leaves Area trends. TLA in *C. comosum, S. wallisii* and *M. spicata* with the seven growing media. The x axis represents the days and the eight measurement days are reported. The y axis reports the TLA registered and the different ranges depend on the plant species.

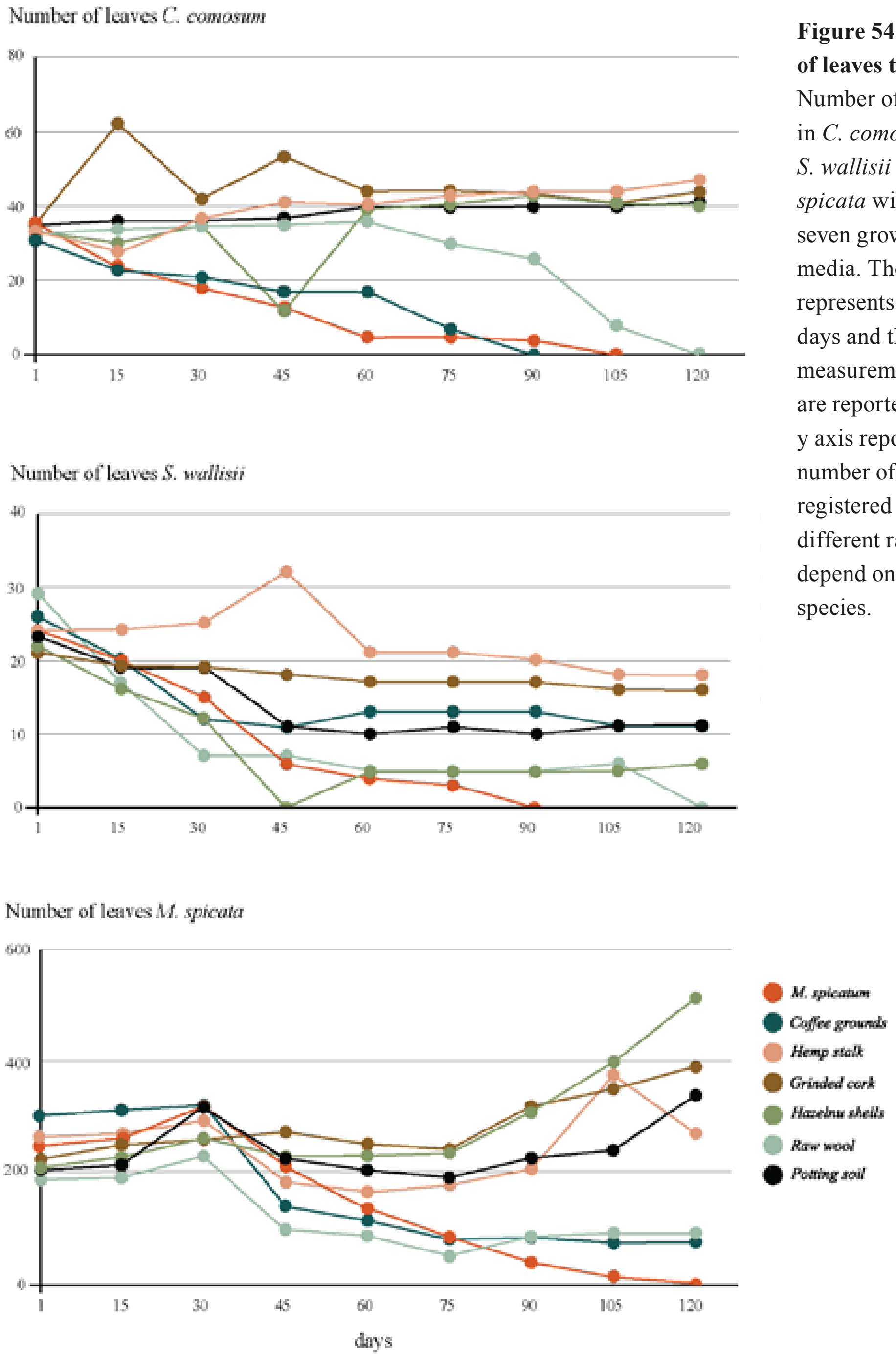


Figure 54. Number of leaves trends. Number of leaves in *C. comosum, S. wallisii* and *M. spicata* with the seven growing media. The x axis represents the days and the eight measurement days are reported. The y axis reports the number of leavest registered and the different ranges depend on the plant species.

	TLA_i (cm^2)	TLA_f (cm^2)	nl_i	nl_f	MLGI
		C. comosum			
	TLA_i (cm^2)	**TLA_f (cm^2)**	**nl_i**	**nl_f**	**MLGI**
M. spicatum	1716,42	0,00	34	0	-
Coffee grounds	1367,17	0,00	31	0	-
Hemp stalks	1450,03	1939,40	33	47	-2,68
Grinded cork	1400,99	2143,49	34	44	7,51
Hazelnut shells	1497,28	1801,33	34	40	1,00
Raw wool	1415,98	0,00	33	0	-
Standard potting soil	**1557,24**	**1844,33**	**35**	**41**	**0,49**
		S. wallisii			
	TLA_i (cm^2)	**TLA_f (cm^2)**	**nl_i**	**nl_f**	**MLGI**
M. spicatum	590,00	0,00	24	0	-
Coffee grounds	1480,00	201,95	26	11	-3,87
Hemp stalks	800,00	2746,64	24	18	11,00
Grinded cork	510,00	536,01	21	16	4,93
Hazelnut shells	450,00	187,72	22	6	3,10
Raw wool	600,00	0,00	29	0	-
Standard potting soil	**560,00**	**330,48**	**23**	**11**	**2,44**
		M. spicata			
	TLA_i (cm^2)	**TLA_f (cm^2)**	**nl_i**	**nl_f**	**MLGI**
M. spicatum	1530,00	0,00	247	0	-
Coffee grounds	1310,00	332,19	301	76	0,06
Hemp stalks	1690,00	2003,59	263	270	1,03
Grinded cork	1590,00	3480,18	224	388	1,92
Hazelnut shells	1200,00	5270,83	210	512	4,58
Raw wool	1090,00	229,10	186		-3,37
Standard potting soil	**1160,00**	**3102,40**	**205**	**338**	**3,52**

Table 6. The table shows the TLAi, TLAf (cm2), nFi, nFf and the MLGI (cm2) values of the seven growing media for C. comosum, S. wallisii and M. spicata. MLGI values higher than the reference value of the standard potting soil are highlighted in yellow.

based medium, as well as in raw sheep wool-based and coffee grounds-based growing media, underwent a drastic reduction in chlorophyll content starting from the 30th day of the experiment.

3.5.4 Plants growth in response to different growing media

The results from the two-way ANOVA analysis consistently demonstrated the impact of the seven different growing media on both the TLA and the number of leaves across all three plant species. Significant variance was observed among the seven treatments within the three plant species, among the various growing media, and between these two factors ($\alpha < 0.5$).

Table 6 provides an overview of the MLGI for each substrate and plant species. Notably, all plants cultivated in *M. spicatum*-based growing media perished before the conclusion of the monitoring period. A similar outcome was observed for *C. comosum* when grown in coffee grounds-based and raw sheep wool-based growing media, as well as for *S. wallisii* in raw sheep wool-based growing media. For a deepen understanding of plants response, Figure 53 and Figure 54 show the trends of TLA and number of leaves for each combination of plant speices and alternative growing medium.
For *C. comosum*, the MLGI exceeded that of the potting soil when cultivated in grinded cork-based and hazelnut shells-based growing media, while the hemp stalks-based growing media yielded a negative MLGI. In particular, the MLGI associated with grinded cork-based growing media displayed the highest value, surpassing that of the potting soil by more than seven times.

S. wallisii exhibited a negative MLGI only when grown in coffee grounds-based substrate. The MLGI for grinded cork-based and hazelnut shells-based growing media were relatively similar and higher than the potting soil. However, the MLGI in hemp stalk-based growing media was notably higher, reaching almost five times that of the potting soil.

As for *M. spicata*, a negative MLGI was observed when cultivated in raw sheep wool-based growing medium. While the MLGI for coffee grounds-based, hemp stalks-based, and grinded cork-based growing media displayed positive values, they were lower than that of the potting soil. Hazelnut shell-based growing media was the exception, with an MLGI surpassing that of the potting soil.

3.6 Discussions

The following section 3.6.1 provide an in-depth examination of the outcomes derived from the physical and chemical characterization of the diverse growing

	C. comosum				
	MLGI (cm^2)	**Chlorophyll c. ($\mu mol\ m^{-2}$)**	**Water demand (ml)**	**Bulk density ($g\ cm^{-3}$)**	**Volume stability (%)**
M. spicatum	-	113,1	1800	0,25	50%
Coffee grounds	-	142,6	1800	0,42	70%
Hemp stalks	-2,68	397,4	3000	0,29	85%
Grinded cork	7,51	372,9	2400	0,3	90%
Hazelnut shells	1,00	426,6	3600	0,48	85%
Raw wool	-	278,2	1500	0,04	40%
Standard Potting soil	0,49	411	3300	0,52	70%
	S. wallisii				
	MLGI (cm^2)	**Chlorophyll c. ($\mu mol\ m^{-2}$)**	**Water demand (ml)**	**Bulk density ($g\ cm^{-3}$)**	**Volume stability (%)**
M. spicatum	-	399,5	1800	0,25	50%
Coffee grounds	-3,87	449,3	1800	0,42	70%
Hemp stalks	11,00	1139,1	3000	0,29	85%
Grinded cork	4,93	1297,2	2400	0,3	90%
Hazelnut shells	3,10	507	3600	0,48	85%
Raw wool	-	351,8	1500	0,04	40%
Standard Potting soil	2,44	847,4	3300	0,52	70%
	M. spicata				
	MLGI (cm^2)	**Chlorophyll c. ($\mu mol\ m^{-2}$)**	**Water demand (ml)**	**Bulk density ($g\ cm^{-3}$)**	**Volume stability (%)**
M. spicatum	-	429,2	2000	0,25	40%
Coffee grounds	0,06	641,3	1500	0,42	70%
Hemp stalks	1,03	840,1	3500	0,29	75%
Grinded cork	1,92	858,7	3000	0,3	90%
Hazelnut shells	4,58	830,9	3500	0,48	80%
Raw wool	-3,37	722,8	2000	0,04	30%
Standard Potting soil	3,52	891,7	3500	0,52	70%

Table 7. Multi-criteria matrix.
The matrix showing results of each growing medium for *C. comosum*, *S. wallisii* and *M. spicata*. Higher values than potting soil are highlighted in green.

media. Subsequently, Sections 3.6.2 - 3.6.8 delves into growing media performance based on the criteria for assessing the sustainability and efficacy of these growing media.

3.6.1 Optimising growing media physical and chemical characteristics

The analysis of the growing media characteristics reveals that augmenting potting soil with a 50% inclusion of bio-resources helps maintain a stable pH level suitable for floricultural applications. With regards to Total Porosity, most alternative media met the accepted criteria, with the exception of the coffee grounds-based and *M. spicatum*-based substrates, which only marginally attained the 50% threshold. In contrast, hazelnut shells-based growing media exhibited a TP akin to that of potting soil.

In terms of WHC, the other alternative growing media displayed exceptionally high values, which may pose potential issues as they could lead to overwatering and potentially harm the plants, despite efforts to maintain irrigation based on humidity levels. It is noteworthy that lignin-based media exhibited the lowest EC. However, apart from hazelnut shells and cork-based media, the remaining alternatives registered EC values exceeding 1100 µS/cm, a threshold considered acceptable for floricultural purposes according to Dewir et al. (2005).

These findings, stemming from the characterization of the growing media, are indeed promising, particularly when considering the experimental phase of the proposed media. They underscore the potential viability of these alternatives for supporting plant development and warrant further testing and evaluation.

3.6.2 Comparative analysis between alternative growing media and the potting soil

The subsequent sections delve into the outcomes achieved by each of the alternative growing media in conjunction with *C. comosum, S. wallisii*, and *M. spicata*, while making comparative assessments against the reference potting soil. These results are systematically presented through a multi-criteria matrix, meticulously crafted to underscore the strengths and weaknesses of each growing medium concerning its compatibility with the aforementioned plant species.

Referring to Table 7, the criteria employed encompass the MLGI and chlorophyll Content, reflective of plant growth and hcalth. Concurrently, factors like water demand, bulk density, and volume stability are utilized to gauge the performance of the growing media. While the former two criteria provide insights into the efficiency of the alternative growing media in nurturing herbaceous and ornamental plants, the latter three criteria are instrumental in evaluating the sustainability of the growing media.

As depicted in Table 7, the multi-criteria matrix serves as project-oriented tool, facilitating straightforward comparisons between diverse growing media and plant species. It also serves to highlight instances where certain growing media outperform the traditional potting soil, in alignment with the principles advocated by Alexander and Bragg (2014). Below the performances of each growing medium for each plant species are discussed.

3.6.3 M. Spicatum-based growing medium

This particular growing medium exhibited an exceptionally low bulk density, making it particularly well-suited for applications that demand high vegetation coverage, particularly in wall-based installations. However, its significantly low water demand can be attributed to the notably high WHC it possesses, which, regrettably, may have contributed to root rot issues encountered across all three plant species. The elevated porosity and the inherent inconsistency in the composition of the crushed *M. spicatum*, coupled with its high WHC, have likely contributed to its diminished volume stability. Consequently, this characteristic raises concerns about its feasibility in real-scale VGS applications, as it would necessitate frequent substrate replacements, leading to a resource-intensive and potentially unsustainable practice, as highlighted by Six et al. (2016).
Nonetheless, the positive aspect to consider is the remarkable lightweight nature of this growing medium. This characteristic opens the door to the possibility of blending this material with another growing medium possessing complementary traits, which could help offset the excessive water retention capacity of the *M. spicatum*-based substrate, making it a more viable option for practical vertical greenery systems implementations.

3.6.4 Coffee grounds-based growing medium

This growing medium displayed commendable volume stability akin to standard soil. However, similar to the M. spicatum-based growing medium, its low water demand accentuates its tendency towards excessive water retention, a characteristic that led to root rot issues across various replicates, irrespective of plant species. These findings align with those of Hardgrove and Livesley (2016), who observed that water retention increased when coffee grounds were directly incorporated into soil. Furthermore, insights from Chrysargyris et al. (2021) emphasized that the addition of coffee grounds diminished the air-filled porosity of peat-based growing media, necessitating modest quantities and more frequent watering to prevent symptoms of over-irrigation.

In light of these challenges, the remarkably high WHC recorded for the coffee grounds-based growing medium makes it more intricate to regulate watering effectively. Consequently, this growing medium might not be deemed a suitable standalone alternative to traditional soil. Nonetheless, its commendable performance in terms of volume stability hints at the possibility of blending it with other growing media to create an effective growing media that can balance the water retention characteristics associated with spent coffee grounds.

3.6.5 Hemp stalks-based growing medium

The physical characteristics of this alternative growing medium exhibited superior performance in most criteria compared to the conventional soil. However, it's important to note that hemp stalks-based growing medium yielded species-specific results. In the case of *C. comosum*, the outcomes were less promising in terms of plant growth performance, suggesting a potential insufficiency in nutrient supply offered by this growing medium for the tested plant species. This observation aligns with the findings discussed by Aurdal et al. (2022), indicating that wood fiber-based growing media offer physical stability but often require supplementary nutrients, which could potentially hinder the growth of *M. spicata*.

Conversely, the notably positive results obtained in the plant growth of *S. wallisii* underscore the suitability of the hemp-based growing medium for this specific plant species. It exhibited the highest results in the MLGI across all replicates tested, indicative of its compatibility with *S. wallisii*. This outcome resonates with previous research highlighting the low nutrient demand of S. wallisii, as documented in various studies (Dewir et al., 2005; Mak & Yeh, 2001).

The hemp canapule-based growing medium emerges as a promising alternative solution to standard growing media, particularly for *S. wallisii*, when considering the results across all five criteria in the multi-criteria matrix.

3.6.6 Grinded cork-based growing medium

It showed good results regarding substrate physical characteristics and plant biomass growth, specifically for *C. comosum* and

S. wallisii. In particular, *S. wallisii* showed the highest chlorophyll content among all the alternative growing media and this result suggests the suitability of lignin rich materials as growing media amendments for this specific plant species (Graceson et al., 2014). Also MLGI values for *C. comosum* and *S. wallisii* suggested that the good performance related to plant growth can be due to the high porosity of the corkstructure (Bozzolo & Evans, 2013), ensuring air provision to the rooting system(Liang et al., 1996).

3.6.7 Hazelnut shells-based growing medium

This particular growing medium exhibited a more favorable impact on leaf growth in all three tested plant species when compared to standard soil. Notably, it delivered positive results for plant growth and health, particularly evident in *C. comosum*. These findings align with the results reported by Ekbic et al. (2022), highlighting the effectiveness of the nutrients provided by hazelnut shells in promoting chlorophyll production in *C. comosum*. Furthermore, the lignin content in this alternative growing medium contributes to its excellent volume stability, ensuring adequate air provision to the root system, as supported by Gruda (2019). This factor holds particular significance for the growth and health of *C. comosum* (Rameshkumar, 2018).

The multi-criteria matrix reveals that the hazelnut shells-based growing medium required more watering than standard soil, indicating efficient substrate drainage. This characteristic offers valuable insights into the strong performance observed in the growth of *S. wallisii* (Mashinchian et al., 2017). However, when considering the water demand observed in *M. spicata* in an outdoor environment, the hazelnut shells-based growing medium exhibited similar water requirements to standard soil, reflecting comparable moisture retention capabilities.

3.6.8 Raw sheep wool-based growing medium

Performances obtained by this alternative growing medium presented very similar trends to those obtained by *M. spicatum*-based substrate. Data reported in Table 7 demonstrate that this growing medium is not suitable to support plant growth. In fact, the low water demand suggests that this waste presents a high-water retention capacity that may induce root rot in all replicates of the three plant species and in particular it was responsible for the death of all *C. comosum* and *S. wallisii* replicates. Moreover, the extreme low volume stability of this growing medium does not assure a consistent structure to the rooting systems. In fact, it slowly disaggregated into their two components during irrigation, separating regular soil from raw sheep wool. Therefore, implementation in substrates treatment and preparation must be considered in order to significantly evaluate raw sheep wool as components for alternative growing media. Although Gabrys and Fryczkowska (2022) didn't specify the nature of the standard cultivation substrate used in their experiment, it could be suggested that their results depended on the proportion of regular soil and wool used in the two studies, or on the different physical performance of dust wool. Nevertheless, the high lightness of this waste and its water holding capacity is promising for vertical greening applications suggesting the opportunity to mix it with other growing media whose characteristics could balance the harmful water retention and stabilise the volume structure.

3.6.9 Research takeaways and future developments

Hazelnut shells-based and cork-based growing media, when paired with *C. comosum* and *S. wallisii*, and hemp stalks-based growing medium with *S. wallisii*, demonstrated superior performance compared to traditional potting soil. These results indicate their potential as promising and sustainable growing media for vertical greenery systems. These findings underline the suitability of lignin-rich materials as effective growing media amendments for the tested plant species, providing crucial insights for the utilization of local lignin-rich bio-resources in various geographical contexts. Notably, grinded hemp stalks exhibit the advantage of requiring no pre-treatment before being incorporated into potting soil, positioning them as a readily applicable bio-resource for the development of locally produced, sustainable growing media.

Furthermore, all alternative growing media exhibited favorable characteristics in terms of volume stability, lightweight properties, and water consumption when compared to potting soil. This makes them compelling choices as amendments for creating lightweight, durable, and low water-demanding vertical greenery systems growing media. Consequently, it is strongly recommended that further studies delve into these growing media, varying the material mix percentages within the experimental protocol (Williams et al., 2022). In fact, it is unlikely that growing media composed of different percentage of the same bio-resource and standard growing media would show identical performance. Moreover, to assess the effectiveness of the proposed alternative growing media, it is fundamental to undergo this experimental protocol with the proposed bio-resources from other geographical contexts. It is reasonably predictable that results would more or less change according to contextual characteristics of the bio-resource from other regions and different treatments received. In the present work, the context-specific results are the main takeaways, nevertheless these results also highlighted some interesting bio-resources worth to be tested in other countries. This is a fundamental future step in order to expand the outcomes of the developed experimental research. For this purpouse the developed multi-criteria matrix can be applied also to compare alternative growing media composed of same bio-resource in different percentage or from different regions.

Comprehensive chemical and biological assessments should be performed to gain a more thorough understanding of the attributes of these alternative growing media. In addition, further data analysis and testing are essential to enhance and expand upon the outcomes achieved in this study.

These studies should develop a broader characterization of innovative organic growing media, encompassing physical, chemical and biological tests. This approach can provide a more comprehensive evaluation of the properties and characteristics of these alternative growing media. Furthermore, future studies should prioritise the assessment of nutritional values and other chemical properties of these growing media to identify the main nutrients available for plant growth and to design suitable fertigation strategies.

The reutilization of these bio-resources and the establishment of a novel supply chain rooted in circular bioeconomy principles for vertical greenery systems have the potential to stimulate innovative advancements in vertical greening within the Mediterranean region and other areas where the bio-resources studied in this research are readily available. The outcomes of this research underscore the necessity to prioritize growing media for enhancing the sustainability of vertical greenery systems and nature-based solutions in general, given their increasing prevalence.

The multi-criteria matrix provided in this study serves as a foundational description of alternative growing media. Its further development should incorporate additional properties and substrate characteristics. Additionally, the methodology outlined in this study, which combines sustainable design thinking, circular bioeconomy principles, and laboratory experimentation, can guide the vertical greenery systems design process by helping identify promising sustainable alternatives to conventional growing media. The applicability of this methodology is envisaged in other geographical contexts, fostering collaboration between academics and practitioners. Its regional or national implementation would require the interdisciplinary engagement of local companies, research centers, universities, architects and landscape designers. This approach promotes a sustainable production system for vertical greenery systems growing media based on research into the valorization of bio-resources at the local level.

Thus, the multi-criteria matrix is a promising guiding tool for the selection of the most suitable growing media - according to the context and the identified requirements - and for the design of new experimental sets.

The application of design-by-components principles to a bio-inspired system, such as the green wall, emphasizes the crucial role of plants as the central element of the system. The design should be guided by the requirements for the healthy growth of plants, thus by the requirements of the coupled component of “plant + growing medium.”

A key strategy to align vertical greenery systems with current design paradigms is to design a growing media that promotes optimal plant development while minimising environmental impact (Ascione et al., 2020). To maximise vegetated area of a green wall, it is essential to plan a reduction in the system weight wherever feasible. This study proposes the use of lighter materials or reducing material replacement as promising strategies. This approach decreases the weight of the soil component bringing also to reduction of the weight of the anchoring system, thereby lessening the overall environmental impact of the greenery system (Oquendo di Cosola et al., 2020). The initial optimization of the plant-growing media component sets the stage for optimizing the entire system, promising a reduction in environmental impacts. Ultimately, conducting an environmental life cycle assessment for each growing medium studied in this research can offer a comprehensive understanding of the best strategies to enhance the sustainability of vertical greenery system design.

Chapter 4

Social benefits of vertical greenery systems

Empirically exploring thier influence
on the perception of space

Synthesis of the chapter

Assessing the intangible social benefits of green walls remains a research gap. To address this, a socio-ecological approach was employed in this research to evaluate the restorative effects of green walls in Turin (taly) and Lisbon (Portugal). The research combined naturalistic observation and surveys to analyze the technical, spatial, and social aspects of the sites. A self-rating questionnaire based on the Perceived Restorative Scale model was administered to 330 participants. The Green Walls Perceived Restorativeness Scale included 17 items covering factors like Familiarity, Fascination, Extent and Coherence, Being-away, and Preference. The results indicate that green walls have a high perceived restorative capacity, attracting people to congregate and influence urban space use. This study contributes a methodological framework to bridge the research gap on the social benefits of green walls, guiding evidence-based biophilic urban design and urban policy development. It also provides valuable data for assessing the cultural ecosystem services of green walls and their overall sustainability in cities.

4.1
Expanding the knowledge on VGSs social benefits

The rapid urbanization we are witnessing today has raised significant environmental and social concerns, posing challenges to both human well-being and urban sustainability. In response to these challenges, innovative urban greening concepts inspired by nature are emerging as pivotal elements in the design, construction, and revitalization of urban spaces, reshaping the very notion of urban green areas (Dorst et al., 2019).

As discussed before, functioning as nature-based solutions, vertical greenery systems represent versatile infrastructure alternatives that offer a multitude of environmental and social benefits concurrently (Goel et al., 2022).

Extensive research suggests that strategically integrating vertical greenery systems into urban landscapes can support the restoration of ecosystem processes, including the cultural ecosystem services (Sang et al., 2022).

Figure 55. Green walls create an opportunity of interaction with people.

It's noteworthy that the focus of research on green walls, until recently, has primarily centered on their contributions to regulating ecosystem services at the building and neighborhood levels (Chafèr et al., 2020). However, over the past decade, there has been a growing interest in the potential of vertical greenery systems to enhance urban social well-being. This shift is attributable to the increasing recognition of the significance of social sustainability in urban areas (Sugandha et al., 2022) and the global push for greener urban environments, prioritizing the livability of cities and the health and well-being of their residents as urgent concerns. Urban green strategies and initiatives have gained significant traction, as the capacity of urban green infrastructures to enhance the overall quality of urban life is now widely acknowledged. However, the challenges of land scarcity and intensive urban development have rendered traditional ground-level interventions less practical. Consequently, over the last three decades, green walls have evolved into adaptable solutions, effectively introducing greenery into the urban landscape potentially transforming the relationship of people with nature in cities

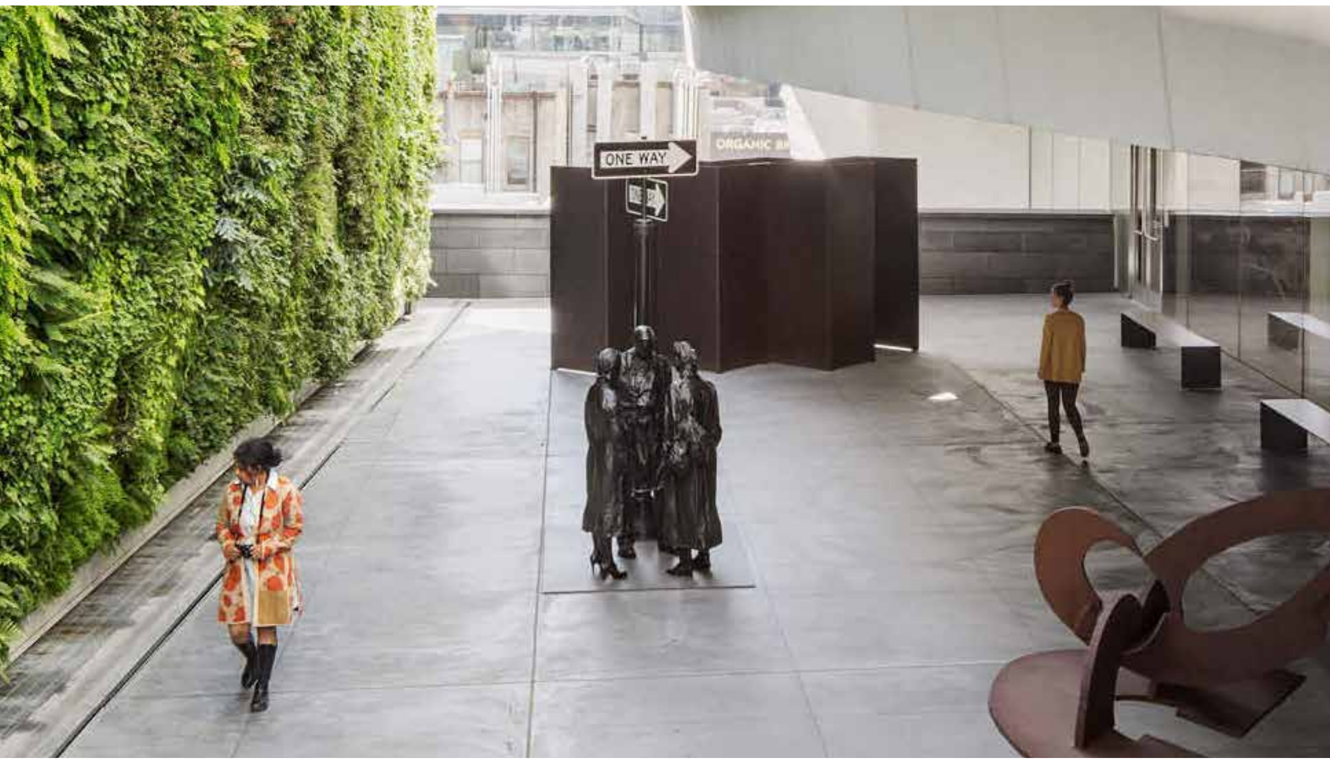


Figure 56. Biophilic design works on natural elements improving user wellbeing.

(Douglas et al., 2021).

Stepping into the realm of biophilic design (Fig 56), which entails incorporating natural elements into urban spaces, it is imperative to consider people's perceptions and emotions to provide physiological and psychological benefits (Berto et al., 2022). However, assessing the intangible advantages stemming from interactions with vegetation and green infrastructures, such as psychological well-being, remains a burgeoning field of research (Chafèr et al., 2020). Furthermore, since green walls represent a form of technological greenery, they cannot be evaluated in the same manner as traditional urban green interventions (Dover, 2017). Therefore, their effects on individuals' perceptions necessitate specific investigation to guide effective biophilic design.

Reviewing academic research that delves into the examination and evaluation of the social advantages offered by green walls, it becomes evident that the majority of these studies have emerged over the past decade. In these investigations, the primary focus is on people's perceived well-being resulting from direct or indirect interactions with green walls. The study participants typically fall into specific categories, such as university students, schoolchildren, or clinic and hospital patients (van den Berg, 2017; Pérez-Urrestarazu et al., 2017). In some of these studies, the sense of well-being generated by green walls is assessed through people's aesthetic appreciation, with Magliocco and Perini (2018) highlighting how the degree of aesthetic appreciation can influence a person's interest in the green wall. The work of Petra et al. (2022) demonstrates that a person's visual perception of the biodiversity of a green wall increases aesthetic appreciation and the sense of pleasantness.

Studies focusing on quantifying the social benefits offered by green walls employ divergent methodologies to evaluate the well-being derived from people's interactions with them.
Some studies concentrate on quantitative measurements of stress reduction by monitoring biometric parameters like heart rate, blood pressure, and salivary alpha-amylase (Sedghikhanshir et al., 2022; Grilli & Sacchelli, 2020). Others investigate the perceived state of well-being qualitatively, employing questionnaires or conducting face-to-face interviews (Minova et al., 2020). Thus research in this field is clearly divided into two topics: health and perceived well-being. In the first category, the dependance of green walls influence on health can be linked to the environmental benefits that these systems offer at the micro urban scale. Instead, the perceived well-being represent a complex issue, as an independent benefits not directly related to the enviromental benefits of green walls. As a proof of this complecity, in the works where people's subjective opinion and perception are involved, it is interesting to note how different intangible concepts of well-being become part of the social benefits investigation, i.e pleasantness, liveability, perceived mental relief, sense of connection with nature, sense of place. Within this body of work, studies by Lotfi et al. (2020) and Timm et al. (2018) employ a qualitative approach using questionnaires to assess psycho-physiological benefits. They utilize the Perceived Restorativeness Scale (PRS), a well-established tool in social and natural sciences, to gauge the sense of comfort and mental relief stemming from experiencing a specific environment. This scale involves self-assessments answered using a semi-qualitative scale, typically the Likert scale. Notably, these studies by Lotfi et al. (2020) and Timm et al. (2018) evaluate people's perceived restorativeness in the context of indirect and virtual experiences with green walls. Participants assess window views and virtual representations of buildings featuring green walls. However, as noted by Ziesel (1981), the direct experience of an environment provides more behaviorally informative data.

Given the experiential nature of Perceived Restorativeness, analyzing people's perceptions of green walls in real environments can yield crucial insights into their social benefits (Mouratidis & Poortinga, 2020). The significance of investigating physiological and psychological responses to the direct experience of green infrastructures is emphasized by the growing number of

works that develop increasingly accurate visual reconstructions and immersive experimental setups (Matos Silva et al., 2023; Llaguno-Munitxa et al., 2022; Yau-Huo et al., 2019).
Nevertheless, there remains a significant research gap in field investigations of the social benefits of green walls (Browning et al., 2014). This information could be instrumental in guiding evidence-based biophilic designs for urban spaces (Figure 57). The current study contributes to the exploration of the social benefits of green walls within urban environments by collecting primary data on people's Perceived Restorativeness within two specific contexts featuring green walls. These contexts are located in Turin (Italy) and Lisbon (Portugal), and the study compares their restorative capacity (Hartig, 2021). Through the quantification and comparison of Perceived Restorativeness in these two green wall settings, the paper aims to identify design and spatial factors that influence citizens' perceptions and preferences. This understanding can be invaluable for guiding the biophilic design of urban projects that incorporate green walls.

Furthermore, the present work seeks to establish a systematic method for detecting the social benefits of green walls to (i) promote the adoption of evidence-based biophilic design and (ii) include the psychological benefits they offer in the impact assessment of these systems.

4.1.1 Restorative environments

Vegetation have transformative impact on the urban environment, significantly influencing the perception of a context and offering a multitude of benefits for both the environment and the well-being of citizens such as:.

Place Identity - establishment of place identity by enhancing the distinctiveness and character of a location. When green elements are incorporated into the built environment, they become unique identifiers for that place, creating a sense of identity and uniqueness (Rice, 2018).

Sense of Place - The incorporation of vegetation fosters a sense of place, making people feel more connected to the environment. This heightened sense of place is associated with improved well-being and overall satisfaction with the surroundings (Nordh, 2019).

Citizens Attraction - The presence of vegetation has been shown to attract citizens to the areas where they are implemented. People are naturally drawn to lush, green spaces, which can lead to increased foot traffic and social interactions, ultimately improving the vibrancy of urban areas (Kim, et al., 2020).

Increased Fruition - vegetation have the potential to enhance the overall experience of a place, making it more enjoyable and inviting. They offer visual and sensory

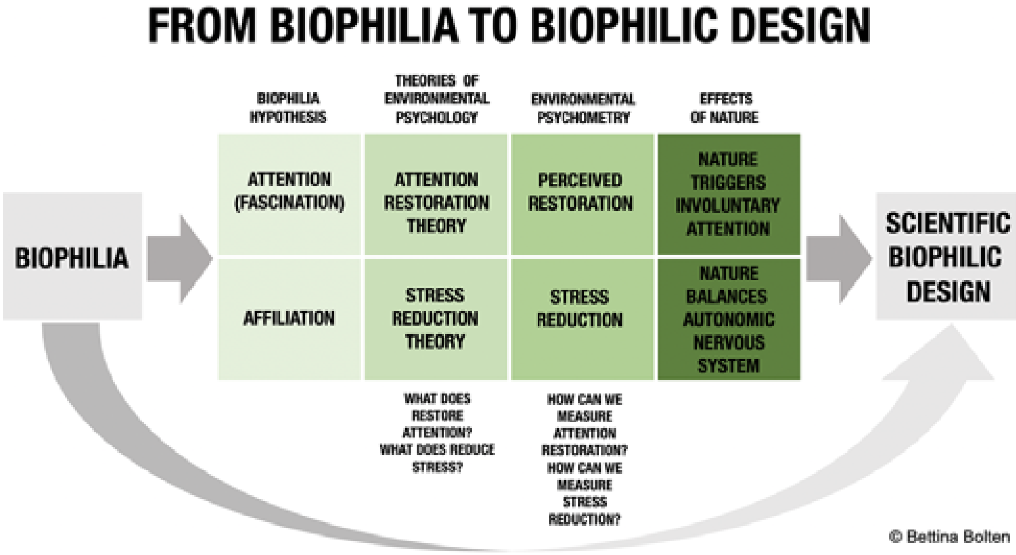


Figure 57. Scientific biophilic design. Framework of scientific biophilic design from Biophilia concept by Bettina Bolten.

stimulation, which can lead to increased utilization of public spaces and improved overall well-being (Kaplan, 2017).

Recent scientific research underscores the transformative impact of vegetation in urban environments, further reinforcing the significance of the theory of Restorative Environments. The theory posits that natural settings, including urban green spaces and urban vegetation, have the capacity to promote psychological restoration and alleviate stress. Recent studies have provided empirical evidence of the restorative effects of green environments, showing how exposure to nature in urban areas can lead to improved cognitive function, reduced mental fatigue, and enhanced emotional well-being (Berto, 2014).
Thus, the presence of greenery in cities goes beyond aesthetics, offering a host of benefits for the well-being of citizens:

Empirical investigation into the potential of green walls as a form of "technological green" to create Restorative Environments is a vital next step in urban design and planning (Figure 58). While the benefits of traditional green spaces in cities are well-documented, the emergence of green walls represents an innovative approach that demands rigorous scientific inquiry (Ergas, 2019).

Figure 58. Restorativeness can be included in cities but its specificity should be investigated.

These investigations will not only expand our understanding of the potential benefits of green walls but also inform urban design strategies, helping cities maximize the well-being of their inhabitants through innovative, nature-infused solutions.

4.1.2 Perceived Restorativeness Scale: origins and development

The PRS serves as a valuable instrument designed to assess how individuals perceive the restorative qualities of their surroundings and experiences, namely is a tool to detect and evaluate Restorative environments It stands as a pioneering effort, being the first of its kind dedicated to measuring the regenerative aspects of various settings.

As a self-assessment tool, the PRS empowers individuals to provide valuable feedback by rating their personal experiences using an 11-point, 7-point, or 5-point Likert scale, offering a nuanced understanding of how individuals relate to their surroundings. Over the years, researchers have made significant contributions to the field of environmental psychology by developing and adapting the PRS to better understand the restorative

qualities of various environments. Today, the PRS exists in different versions tailored to specific contexts and target populations. The development and evolution of the PRS provide a fascinating journey into the intricate exploration of our relationship with the environment.

The creators of the PRS, Hartig et al. (1997), laid the foundation for its application (Figure 59). Their work is grounded in the foundational principles of the Attention Restoration Theory introduced by Kaplan and Kaplan (1989). The original version employs a Likert scale ranging from 1, representing 'not at all,' to 7, conveying 'very much.' This nuanced scale allows respondents to express the depth of their perception regarding the restorative attributes of a particular environment or activity, contributing to a richer understanding of the subject matter. This tool has paved the way for a deeper exploration of how environments influence human well-being.

In the years following its creation, the PRS underwent significant changes driven by two primary objectives. The first aim was to simplify the scale by reducing the number of items, making it quicker and easier to use. The second objective was to make the scale more comprehensive by including factors that would better

Original Perceived Restorativeess Scale (Hartig et al., 1997)

Being Away

1. It is an escape experience.
2. Spending time here gives me a good break from my day-to-day routine.

Fascination

3. The setting has fascinating qualities.
4. My attention is drawn to many interesting things.
5. I would like to get to know this place better.
6. There is much to explore and discover here.
7. I would like to spend more time looking at the surroundings.

Extent

8. There is too much going on.
9. It is a confusing place.
10. There is a great deal of distraction.
11. It is chaotic here.

Compatibility

12. I can do things I like here.
13. I have a sense that I belong here.
14. I have a sense of oneness with this setting.
15. Being here suits my personality.
16. I could find ways to enjoy myself in a place like this

Figure 59. Original PRS. The original version of Perceived Restorativeness Scale, created by Hartig et al. in 1997.

represent the Perceived Restorativeness process, providing a deeper understanding of how people perceive restorative environments. These objectives highlight the ongoing efforts to refine the PRS for both researchers and practitioners.
Over time, different versions of the PRS have emerged, each offering a unique perspective on the restorative qualities of environments. The PRS-11, introduced in 1995, slimmed down the questionnaire to 11 items while retaining the core restorativeness components. The PRS-10, introduced in 2001, streamlined it even further to 10 items while maintaining the core components but merging "extent" and "compatibility" into a single factor for a simpler structure. The PRS-16, launched in 2008, expanded upon the original 16-item scale by introducing novel elements such as "spaciousness" and "complexity" to capture a broader range of restorative qualities. In 2010, the PRS-11 was revised to encompass both natural and built environments, making certain items more versatile and applicable across a wide spectrum of settings. The PRS-5, unveiled in 2015, distilled the scale to just five items, honing in on fundamental facets of restorative experiences. Finally, the PRS-21, introduced in 2016, expanded the scale's horizons to a comprehensive 21-item questionnaire, delving into sensory appeal and naturalness for a holistic understanding of restorativeness.

The various iterations of the PRS reflect an ongoing journey to understand the intricate dynamics of restorative experiences in diverse environments. These adaptations have played a vital role in shaping the understanding of how the environment impacts human well-being and restoration.

4.1.3 Literarture overview on PRS applications

A bibliographic literature review on Scopus identified 99 papers on the PRS published from 1996 to the present. The following research string has been applyied:

TL-ABS-KW ("PRS" **OR** "perceived restorativeness scale")

While the topic saw sporadic publications over the last two decades, there has been a consistent increase in PRS-related studies since 2016, reaching a peak in 2022, which saw a scientific output of 23 papers. While the use of PRS is not yet widespread, the substantial growth in publications in recent years and the continuing upward trend suggest that this area of research is currently in a stage of development (Figure 60). Notably, the number of publications has grown significantly since 2020, which may be linked to psycho-physiological issues arising from the Covid-19 pandemic.

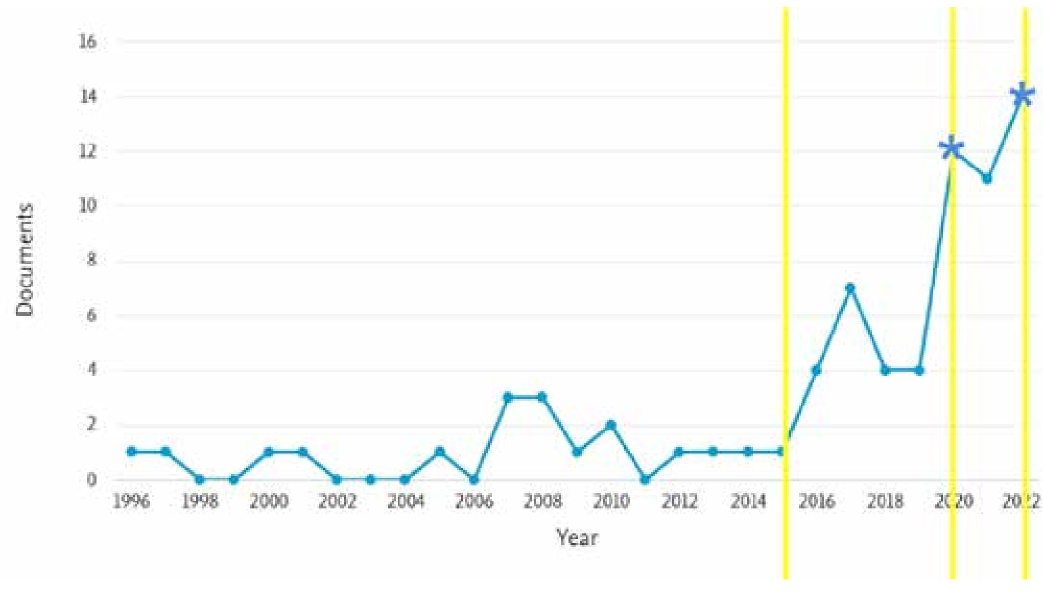
Regarding the geographical distribution of PRS research (Figure 61), the most productive countries in terms of publications are China (20 documents), Italy (16 documents), South Korea (15 publications), and the United States (14 publications). China and South Korea started research in this field earlier, in 2016 and 2017, respectively, while the United States and Italy began their research in 1996 and 2001, respectively.

Among the publications, over half fall within the domain of Environmental Science (31.4%), followed by Social Sciences (15.7%) and Medicine (10%). This distribution highlights the diverse focus of research and academic work in this field.

The majority of publications applied the PRS in experimental activities (approximately 93%). These studies primarily aimed to understand the perceived restorative qualities of various locations. Among these, around 48% focused on examining the Restorative Capacity of open spaces, encompassing both natural and urban environments. Approximately 25% took a comparative approach, seeking to draw distinctions between contrasting situations and locations. About 26.4% centered their focus on the built environment, with a particular emphasis on specific facilities such as homes, hospitals, schools, and universities. A small percentage explored the Perceived Restorativeness of activities (0.3%) and nature-based solutions (0.3%), like green walls and green roofs.

The methods employed in applying the PRS vary. Approximately 67% of the studies used a direct observational approach conducted in-situ, while around 26% assessed participants' perceptions

Figure 60. Temporal evolution. Trends in number of publications dealing with PRS.



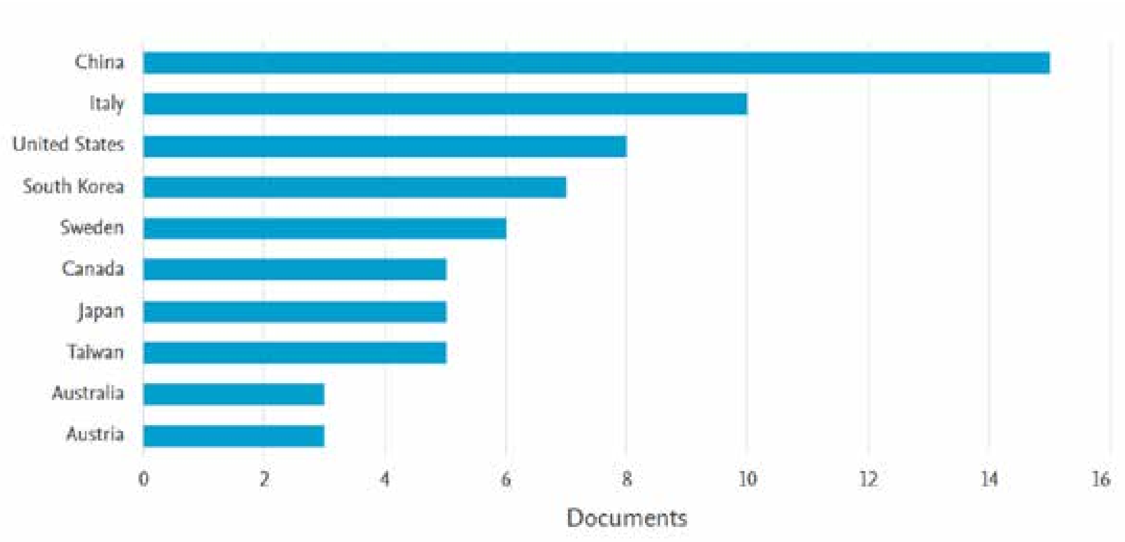


Figure 61. Geographical distribution. Most productive countries for publications dealing with PRS.

and reactions indirectly by presenting them with video simulations or renderings of different locations. One notable study assessed the Restorativeness of a window view.

Additionally, many studies incorporated demographic information as a fundamental component of their investigations, allowing for a more comprehensive understanding of the target group. Variables such as age, gender, and educational and professional backgrounds were commonly used to characterize the composition of participants and interpret PRS results.
While the PRS is generally considered to have reliable empirical validity, researchers often complement it with other instruments or methodologies to enhance the depth of information gathered. Approximately 50% of the studies opted to employ alternative and complementary assessment instruments in conjunction with the PRS. Among these, 33% incorporated self-report instruments primarily focused on psychological investigation, and 17% used biometric monitoring instruments to gather objective data related to physiological responses.

The size of PRS respondents varied, with 30% focusing on groups of 15 to 100 individuals, while 7% engaged with larger participant groups ranging from 300 to 500 individuals. Just one study surveyed more than 1,000 individuals. These numbers reflect the time-consuming nature of survey research methods.

4.2 Exploring green walls Restorativeness

The reserach leverages findings from an analysis conducted at two green walls sites, applying a mixed-method approach. This methodology involved on-site inspections through naturalistic observation (Byrne, 2021), and survey research (Figure 62). A place-based approach has been applied to understand people's behaviours, patterns of urban life and socio-ecological relationships (Mirti Chand, 2018) between people and green walls in the two selected sites: Turin (Italy) and Lisbon (Portugal).

A questionnaire was devised following the PRS model, a well-established tool widely used to assess the potential restorative impact of physical environments, whether natural, urban, or rural (Berto et al., 2018). The incorporation of both naturalistic observation and self-assessment questionnaires aimed to mitigate potential agreement bias in participants' responses by capturing observable data regarding the socio-ecological dynamics between individuals and green walls in the urban context.

Furthermore, socio-demographic data and contextual information have been added to the questionnaire to investigate the target of respondents and interpret their responses. Site inspections and questionnaire distribution were organised in the two sites between November 2022 and May 2023. The data collected were analysed and validated using statistical analysis, following the method applied by other recent studies on PRS (Sella et al., 2023).

Additionally, the aim of the work is to establish a systematic and replicable method to detect the social benefits of green walls, promoting evidence-based biophilic

Figure 62. Methodological framework. Mixed methodology composed of field analysis (naturalistic observation) and survey research (self-rating questionnaire).

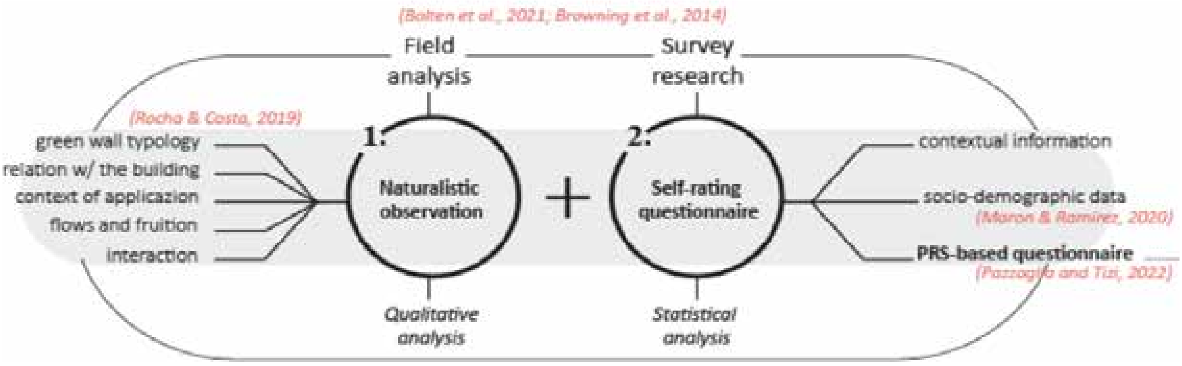


Figure 63. Green walls sites. The front face of the Complesso Aldo Moro (left) and the Centro Cultural de Belem (right).

design adoption and incorporating psychological benefits in their impacts and benefits assessment.

4.2.1 Description of the sites

The chosen site in Turin, the Complesso Aldo Moro (CAM), represents a building complex encompassing office spaces, student facilities, university residences, and commercial establishments (Figure 63). Situated within the historical heart of the city, in close proximity to the University of Turin's main humanities building and some of the city's iconic architectural landmarks, this area serves as a pivotal hub for students to congregate. The CAM complex is the outcome of an urban campus development initiative aimed at fostering an open, integrated network of university structures throughout the urban fabric. An internal courtyard nestled between the buildings was incorporated to host cultural events and social gatherings. Within this complex, two living walls adorn the facades of the main buildings, marking the entrance to the open courtyard (Figure 64). The installation of these green walls aligs with two key themes often central to urban revitalization projects. Firstly, it involves the integration of green infrastructure within educational institutions to enhance the physical and cognitive well-being of students and staff (McCullough et al., 2018). Additionally, it contributes to the urban area's rejuvenation by strategically introducing green infrastructure to enhance overall livability (Dantas et al., 2022).

Figure 64. CAM site. Views of the entrance of the Complesso Aldo Moro in Turin. Fast foods and classrooms of the near University are inclosed in the centre of the city. Green walls are part of the entrance.

Figure 65. CCB site. View of the entrance of the Centro Cultural de Belém in Lisbon. Green walls are barely visible from the entrance on the pedestrian way. Green walls are accessible from the floor.

The selected location in Lisbon is the Centro Cultural de Belém (CCB), a cultural center nestled in the Belém neighborhood in the western part of Lisbon (Figure 65). This district is renowned for its cultural heritage, housing numerous significant Portuguese monuments of both local and national significance. The CCB accommodates a conference center, commercial venues, two auditoriums, and four art galleries for exhibitions. Positioned at the entrance, two living walls are prominently displayed within the inner courtyard, flanking the ticket office (Figure 63). The installation of these green walls is directly tied to the theme of sustainability within museums. The incorporation of green infrastructure within museum settings represents a novel approach to conceptualizing cultural spaces and is currently a burgeoning global trend (ICOM, 2018) that impacts museum management and governance. Figure 63 illustrates the two green walls at the Complesso Aldo Moro in Turin's historic center, as well as the two green walls at the entrance courtyard of the Centro Cultural de Belém in the Belém neighborhood of Lisbon.

4.2.2 Naturalistic observation of the sites

To comprehensively understand the locations of green walls, on-site inspections were conducted at CAM and CCB. The naturalistic observation method was chosen for its discreet information collection from individuals in these environments, following Zeisel's approach in 1981. The goal of these inspections was to uncover similarities and differences to aid in characterizing each location and enhance the interpretation of the Green Wall Perceived Restorativeness Scale (GwPRS) results.

The analysis included technical, spatial, and social dimensions, aiming to identify elements affecting the experience and perception of these spaces, as per Rocha & Costa's work from 2019. Technical observations covered green wall typology and its relationship with the building and surrounding context. Qualitative observations focused on user flows, space usage, and interactions with green walls. This multi-layered approach, advocated by Jalaladdini & Oktay in 2012, was crucial in characterizing the unique features of Lisbon and Turin, enabling a robust comparative study.

4.2.3 Questionnaire preparation and distribution

Figure 66 shows contents and structure of the defined assessment tool. The questionnaire was designed with three distinct sections to gather diverse information:

- **Contextual information** aimed at assessing participants' knowledge regarding the green walls under study and their connection to the selected cities;

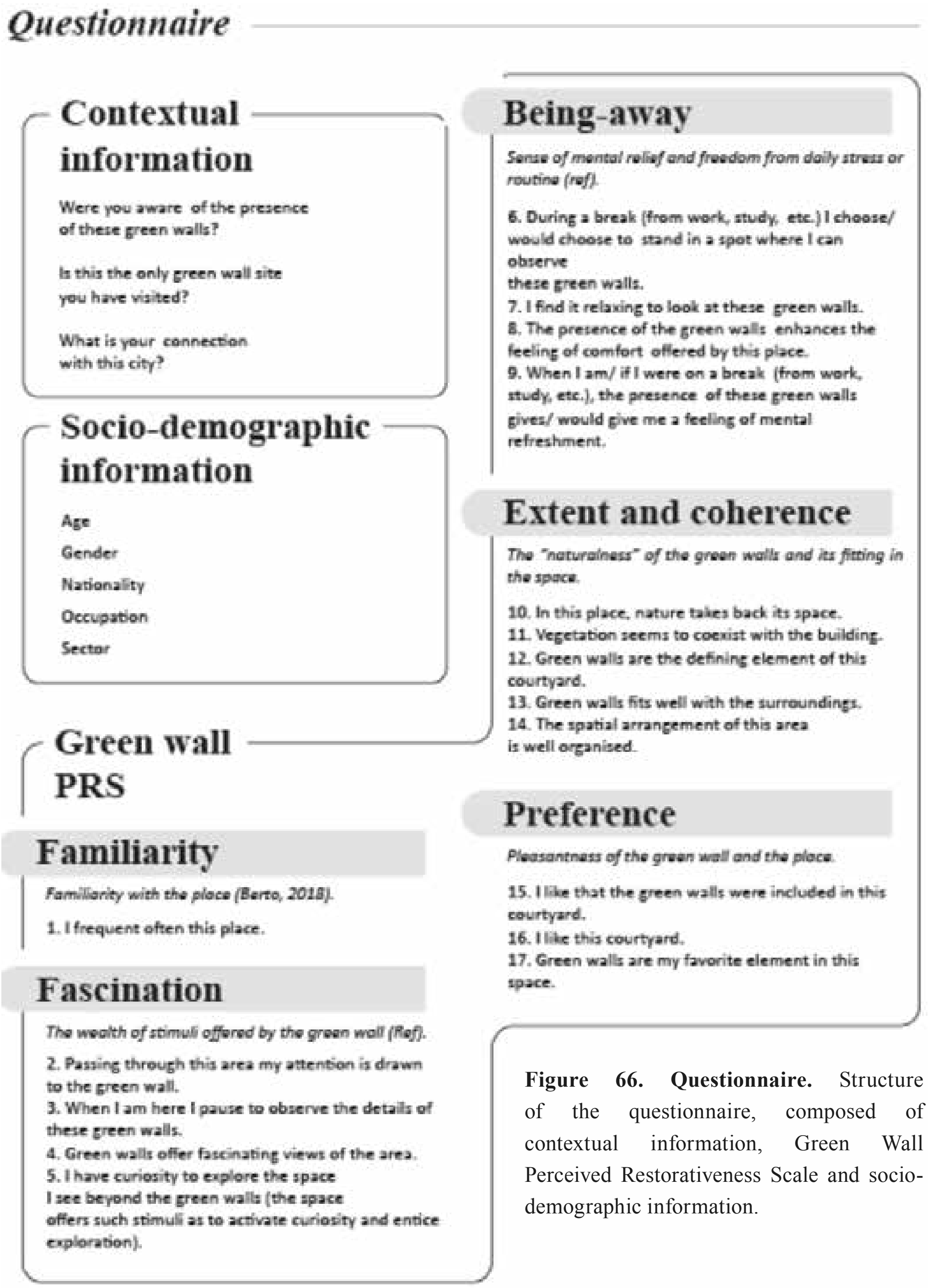


Figure 66. Questionnaire. Structure of the questionnaire, composed of contextual information, Green Wall Perceived Restorativeness Scale and socio-demographic information.

- **General socio-demographic data**, which served to characterize and interpret the responses provided by the interviewees, aligning with the approach of Maron and Ramirez (2020);

- A section based on the PRS, the **Green wall PRS.**

For each site, the questionnaire was adapted into the national languages - Italian and Portuguese - along with English, making it inclusive for foreign participants. Questionnaires were distributed either in printed form or online through a QR code scan, with the online version created using Microsoft Forms. Special attention was paid to ensuring the anonymity of respondents during the questionnaire distribution process.

Drawing on established practices in previous PRS studies, questionnaires were handed out and completed in proximity to the green walls, a method believed to yield more reliable responses reflecting participants' real-time perceptions (Peschardt & Stigsdotter, 2013; Wang & Li, 2022).

Green wall PRS includes several factors: Familiarity (F) with a single item, Fascination (Fa), Being Away (BA), both consisting of four items, Extent and Coherence (EC), composed of five items, and Preference (P), which comprises three items. To streamline the questionnaire for in-person completion, inspiration was taken from Pasini et al. (2014) due to the limited number of items, making it more convenient than the original PRS by Hartig et al. (1996). Furthermore, the adaptation of the original PRS to evaluate the Restorative capacity of green walls reflects a nuanced approach that recognizes the unique influence of "technological" greenery in the built environment. The conventional PRS, initially designed for open landscapes, necessitated modifications to align with the distinctive characteristics of green walls. As expounded by Pazzaglia and Tizi (2022), the inherent limitations of the original PRS in capturing the intricacies of the built environment prompted the need for a more tailored assessment tool.
In this particular study, the refinement process focused on redefining PRS items to specifically gauge the impact of green walls on citizens' perceptions of a given space. Given that the interactions with green walls predominantly occur on a visual level, the adaptation drew inspiration from the comprehensive works of Lotfi et al. (2020) and Takayama et al. (2017). These sources provided valuable insights into the visual aspects and visual appeal of greenery, allowing for the incorporation of relevant items that intricately consider how green walls contribute to the overall aesthetic experience of a space. Moreover , in order to determine the influence of green walls on the perception of a space, items were structured according to a mixed specific and holistic way (Payne & Gustavino, 2018). Indeed, items draw the attention of respondents to the green wall (specific) and their effect in the space (holistic).
Participants used a 5-point Likert scale,

ranging from "I strongly agree" to "I strongly disagree," to express the extent to which a given statement captured their experiences in the setting. Following data collection, these responses were converted into numerical values to facilitate statistical analysis and quantify the Perceived Restorativeness in each site.

4.2.4 Data analysis

The Analysis of Variance was used to evaluate the value of participants' Perceived Restorativeness at the CCB and CAM sites (Simkin et al., 2021). Particularly, a Two-Way ANOVA was conducted, utilizing sites and GwPRS factors as the statistical analysis's factors. Specifically, two levels for sites (CAM and CCB) and five levels for GwPRS factors (Familiarity, Fascination, Being Away, Extent and Coherence, and Preference) were considered. The means and variances of each factor across both sites were compared, along with investigating variations and statistical consistency within and between the values of the factors at the two sites (Masullo et al., 2021).
The hypotheses were formulated:

Null Hypothesis (H01): No statistically significant differences exist in GwPRS factprs among the two sites.

Alternative Hypothesis (Ha1): Statistically significant differences are observed in GwPRS factors and the two sites.

As in the previous work of research (Chapter 3) data for GwPRS responses in the two sites were organized into an Excel spreadsheets, with sites represented as columns and GwPRS factors as rows. Again, the two-way ANOVA analysis was conducted using Excel's "data analysis" tool:
Data > Data Analysis > Two-Way ANOVA with Replications

The analysis generated p-values for each factor and their interactions, allowing for the identification of significant variations in GwPRS factors values based on the sites, and their interactions. Statistical significance was determined at a p-value less than 0.05.

Furthermore, to identify connections among items and their respective GwPRS factors, the Spearman's Ranks Correlation was performed (Liu et al., 2021) using the Likert Scale evaluations of participants of CAM and CCB. For each site, Spearman correlation was perfromed two times, (1) to identify correlations between factors (using Likert Scale evaluations average for each factor) and (2) the correlation between items (using all the Likert Scale participants' evaluations). Furthermore, the reliability and accountability of the GwPRS were assessed for both sites through the application of the Cronbach's alpha test (Pasini et al., 2014). These statistical procedures were conducted using Excel to ensure the generation of robust and consistent results, which complemented the qualitative observations made during the study.

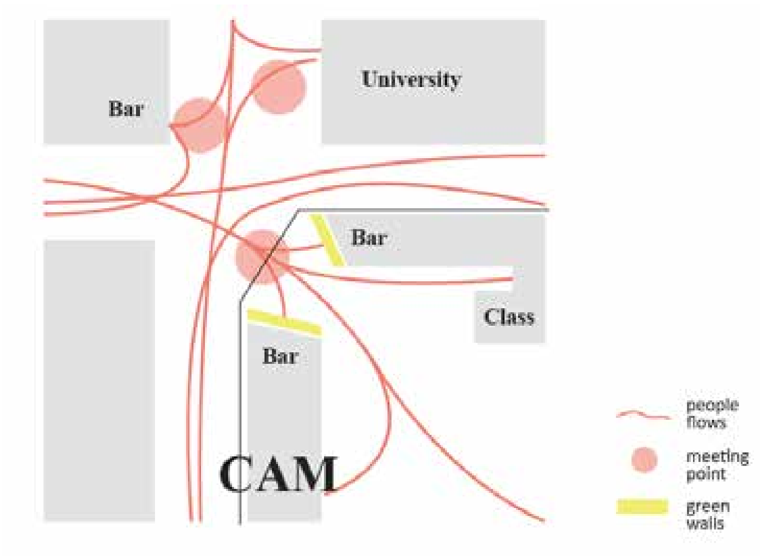


Figure 67. CAM naturalistic observation. Information derived from the naturalistic observation developed in CAM.

4.3 Results of the place-based analysis

The subsequent sections outline the findings derived from both the naturalistic observations and the questionnaire responses at the CAM and CCB sites. These results are categorized into qualitative observations that highlight the technical, spatial, and social attributes of the two sites. In addition, the sections present the qualitative and quantitative responses from the questionnaire, encompassing contextual information, GwPRS outcomes, and socio-demographic data. This analysis is tailored to the specific contexts where green walls are situated, namely the CAM and CCB sites.

4.3.1 Information from naturalistic observation

The CAM boasts two uninterrupted living wall systems adorning the facades of the entrance buildings within the complex. Each of these green walls spans approximately 144 square meters (12 meters by 12 meters) and is positioned on the second level, just above the transparent commercial plinths. These green walls feature a rich assortment of melliferous, trailing, and aromatic plant varieties, resulting in a lush foliage with a diverse range of green shades and colors. The geotextile supporting the plants' root systems is discreetly visible in a few select areas where the foliage is less dense. Both

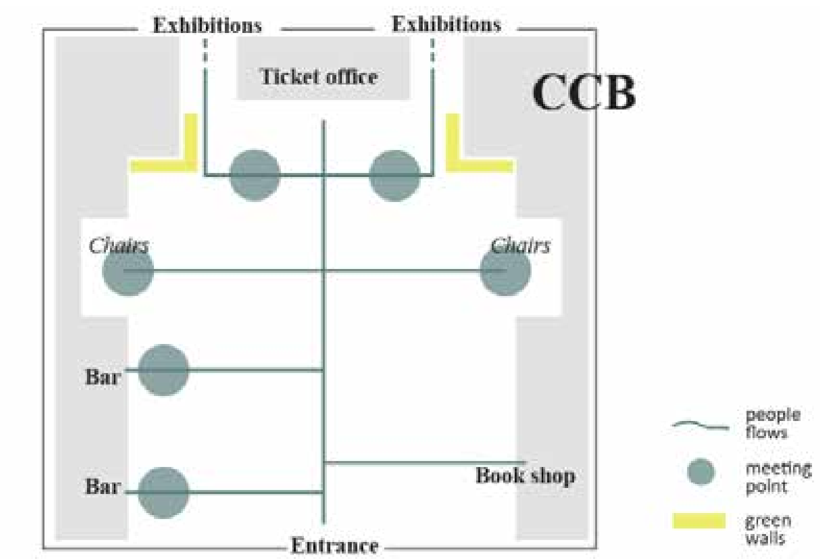


Figure 68. CCB naturalistic observation. Information derived from the naturalistic observation developed in CCB.

green walls are seamlessly integrated into the facades, framed by projecting profiles, with the eaves at the bottom serving as the sole structural component in view. Regarding the spatial layout of the CAM site (Figure 67), the green walls define an expansion in the pedestrian path, guiding visitors towards the inner courtyard. Figure 65 illustrates the primary pedestrian routes, with substantial foot traffic stemming from the intersection of two roads in front of the CAM entrance. Mornings witness a bustling crowd as people commute to their universities and workplaces, while the lunchtime rush sees many people to the nearby restaurants and cafes, many opting for the outdoor seating. Furthermore, students frequently gather during the mornings and afternoons, engaging in conversations and congregating in front of the University and CAM buildings, with some taking advantage of the exterior steps for seating.

At the CCB, two distinct green wall systems, constructed using planter boxes, embellish the surfaces of the slender structures situated at the far end of the entrance courtyard. Positioned in front of the ticket office and the staircase leading to the exhibition spaces, these twin green walls each encompass an approximate vegetated area of 80 square meters (20 meters by 4 meters), adorning two sides of each structure. These green walls initiate from a height of 1 meter and extend to cover the full height of the volumes. Comprised of melliferous, trailing, and aromatic

Age	CAM	Gender	CAM	Nationality	CAM	Education	CAM	Occupation	CAM
18-24	53,20%	Female	75,20%	Italian	95,40%	University	76,10%	Student	58,70%
25-34	20,20%							Employee	24,80%
35-44	6,40%			Romanian	3,70%	High school	22,90%		
45-55	4,60%							Retired	5,50%
55-64	10,10%	Male	23,80%	French	0,90%	Technical certificate			
65-74	1,80%							Freelancer	10,10%
75 or more	0,90%					Junior high school	0,90%	Unemployed	0,90%

Table 9. Target composition of CAM. Information collected from the participants of the survey in Turin.

Age	CCB	Gender	CCB	Nationality	CCB	Education	CCB	Occupation	CCB
18-24	33,90%	Female	59,70%	Portuguese	44,40%	University	83,10%	Student	34,70%
25-34	35,50%							Employee	50,80%
35-44	12,10%			French	12	High school	14,50%		
45-55	11,30%							Retired	1,60%
55-64	4,80%	Male	40,30%	Spanish	9	Technical certificate	1,60%		
65-74	1,60%							Freelancer	12,10%
75 or more	0,80%			Other		Junior high school		Unemployed	0,80%

Table 10. Target composition of CCB. Information collected from the participants of the survey in Lisbon.

plants, both green walls offer a uniform expanse of verdant foliage in a range of green hues, punctuated by vibrant flowers. While the planter boxes forming the green walls remain inconspicuous from the center of the courtyard, a closer inspection reveals their presence. These green walls seamlessly blend into the slender volumes, nestled within a recessed space.

Examining the spatial layout of the CCB entrance courtyard, it serves a dual purpose. On one hand, it houses commercial services and provides areas for meetings and relaxation, complete with chairs and coffee tables. On the other hand, it serves as a gateway to the cultural spaces. As illustrated in Figure 68, the primary foot traffic traverses the entrance and exit pathway of the CCB. The site experiences its highest volume of visitors during holiday periods and weekends, particularly in the afternoons. Weekdays see fewer visitors, but some individuals utilize the courtyard to unwind, grab a cup of coffee at the cafes, or sit at the tables near the green walls. On occasion, visitors even move tables closer to the green walls to enjoy a relaxing break beside them. During site inspections, nearly all visitors passing through the courtyard take notice of the green walls. A substantial portion of these visitors dedicates a few moments to gaze at the green walls, observing, touching, or capturing photographs of these vibrant installations.

	Mean value		Variance			Cronbach's alpha		
Factor	CAM (Turin)	CCB (Lisbon)	CAM (Turin)	CCB (Lisbon)	Total	CAM (Turin)	CCB (Lisbon)	Reference
Familiarity	3,78	2,89	1,38	2,08	1,92			
Fascination	3,88	3,12	0,57	0,30	0,57			
Being-away	4,05	4,19	0,53	0,28	0,41			
Extent and Coherence	3,73	4,00	0,32	0,31	0,50			
Preference	4,13	4,21	0,32	0,32	0,32			
PRS total	3,91	3,68	0,71	0,97	-	0,88	0,78	>0,70

Table 11. Statistical data. Two-way ANOVA and Cronbach's alpha test results of CAM and CCB.

4.3.2 Target composition in CAM and CCB

The GwPRS questionnaire was administered to a total of 230 participants, with 115 individuals in Turin and 115 in Lisbon.

In the case of the CAM site in Turin (Table 9), the vast majority of participants were Italians (95.4%), with a small number of Romanian (3.7%) and French (0.9%) participants. The gender distribution in this group skewed toward females, comprising 73% of the respondents, while males made up 27%. Most participants (89.6%) either lived, worked, or studied in the city of Turin, with only 9.1% residing outside Turin but visiting for leisure, and 1% being tourists. Over half of the participants fell within the 18 to 24 age group (52.2%), while more than a fifth were between 25 and 34 years old (22.9%). Regarding their familiarity with the CAM site, 61.2% of participants were already aware of the presence of the two green walls, and for 21.7%, it was the first time they had encountered a green wall. Notably, 44% of participants saw the CAM as the first site where they had encountered a green wall system. Please refer to Table 1 for a summary of the target composition at the CAM site.

In the case of the CCB site in Lisbon (Table 10), the participant composition consisted primarily of Portuguese individuals (44.4%), with a significant number of French (10.4%) and British (7.8%) participants. The gender distribution showed a slight majority of women at 59.7% and men at 40.3%. A significant portion of the participants (50.8%) were tourists, while 46% either lived, worked, or studied in Lisbon. A smaller portion, 3.2%, lived outside Lisbon but visited the city in their leisure time. In terms of age groups, a slight majority of participants fell within the 25 to 34 age range (35.5%), and 33.3% were between 18 and 24 years old. In relation to their familiarity with the CCB site, 59.7% of participants were aware of the two green walls, and for 51.6%, it was not their first encounter with such a system. Notably, for 48.4% of visitors, the CCB was the first site where they had seen a green wall system. Table 10 summarizes the target composition at the CCB site.

Figure 69.
Evaluations distribution.
Distribution of participants' evaluations of GwPRS in CAM and CCB. The red line refers to CAM results while the blue one refers to CCB results.

4.3.3 Comparing reliability and GwPRS values in the two sites

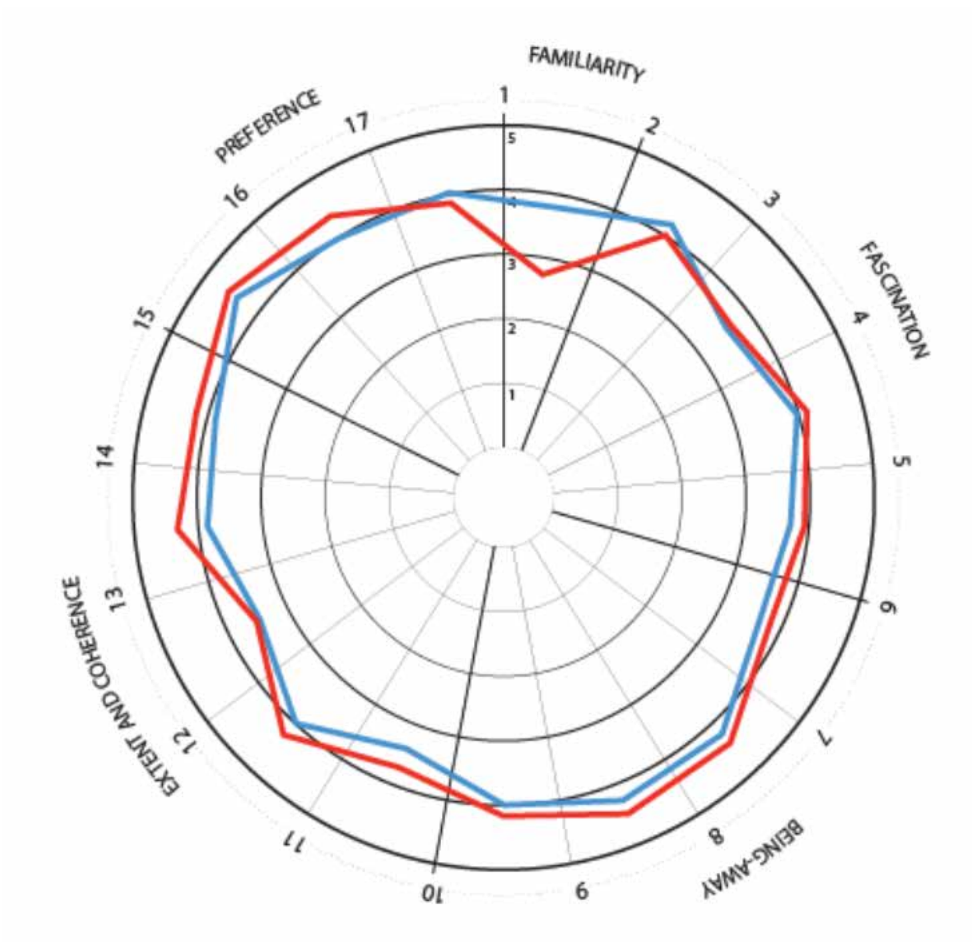
The results of the repeated Two-way ANOVA analysis are presented below, comparing the mean values and variances of factors and items between CAM and CCB. In this analysis, the between-subjects factor pertains to the restorativeness of the place and comprises five levels (F, Fa, BA, EC, P). The within-subject factor has two levels, representing CAM and CCB. Both the between-subjects and within-subject factors demonstrate statistically significant effects.

As an overall summary (Table 11), the average total value of the GwPRS for CCB (67.9) is slightly higher than that for CAM (66.5). CCB exhibits higher values for all factors compared to CAM, except for the F factor. Among all the factors and sites, P stands out as the highest-rated factor, with CCB's P having the highest value. The mean values for BA and P are very similar between the two sites, being the closest among all the factors. Notably, the F factor exhibits the most significant difference between the two sites.

Detailed results of the factors are presented in Table 11. The F factor's mean value for CAM (3.78) is higher than that of CCB (2.98), with a notable difference of nearly 1.00. It exhibits the most substantial difference among the mean values of all other factors. Furthermore, the variance for this factor is significant, being the highest among all factors. In particular, CCB displays a higher variance (2.08) compared to CAM (1.38) and shows the highest variance among all the other factors for both sites.

The Fa factor's mean value for CAM (3.88) surpasses that of CCB (3.12) with a substantial difference of 0.76. While CAM has a higher Fa variance (0.57) than CCB (0.29), the difference in variance is slight, being 0.28. The Fa values and differences between variances are very similar to those of the BA factor. The BA factor for CCB (4.19) has a slightly higher mean value than CAM (4.05) with a marginal difference of 0.14. In this case, CAM's BA has a higher variance (0.53) compared to CCB (0.28), with a slight difference of 0.27. As mentioned earlier, values and differences between variances are very similar to those of the Fa factor.

The EC factor's mean value for CCB (3.73) is higher than CAM (4.00), with a difference of almost 0.27. The variance between the two sites is nearly identical,


FAMILIARITY
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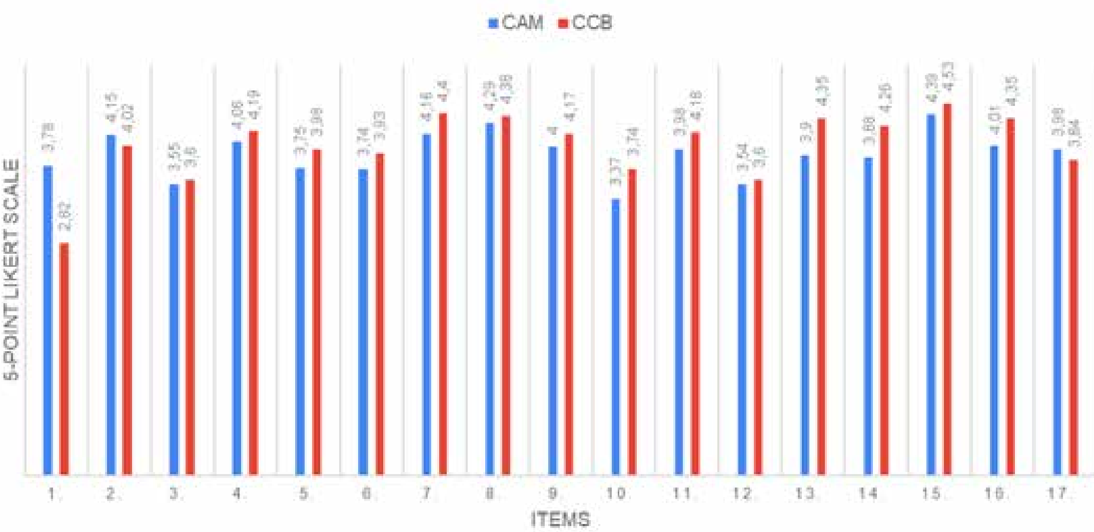
CAM
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	Familiarity	Fascination	Being Away	Ext. and Co.	Preference
Familiarity	1				
Fascination	-0,33	1			
Being Away	-0,41	0,70	1		
Ext. and Co.	-0,27	0,59	0,49	1	
Preference	-0,12	0,49	0,55	0,73	1

Table 12. Factor's correlations. Factors' Spearman correlations for CAM.

	Familiarity	Fascination	Being Away	Ext. and Co.	Preference
Familiarity	1				
Fascination	0,14	1			
Being Away	-0,01	0,50	1		
Ext and Co	0,15	0,43	0,44	1	
Preference	-0,03	0,45	0,48	0,67	1

Table 13. Factor's correlations. Factors' Spearman correlations for CCB.

with CAM (0.32) being slightly higher than CCB (0.31) by only 0.01. For the P factor, the mean values for the two sites are very similar, with CCB (4.21) having a slightly higher mean value than CAM (4.12), resulting in a difference of almost 0.09. This difference is the lowest among all the pairs of factors. Additionally, the P mean value for CCB is the highest among all other factors. The variance for both sites is identical (0.32).

When considering the total variance of each factor, which is the average variance of the variances of the GwPRS factors for each site, it's evident that F has the highest variance (1.92), followed by Fa (0.57) and EC (0.50).

The Cronbach's alpha test confirmed the high reliability of the results obtained. Specifically, the GwPRS conducted at the CAM site achieved a value of 0.88, while the one conducted at the CCB site scored 0.78 ($\alpha > 0.70$), as per Pasini et al. (2014).

Regarding the distribution of evaluations for the two green wall sites, it is evident from Figure 69 that the mean values of items are generally consistent between and within CAM and CCB, with one exception being the evaluations for item 1, "I frequent this place often" (CAM = 3.78; CCB = 2.82).

When considering the items, both sites received average ratings mostly above 4 ("I agree"). CCB consistently had higher

	1. I frequent this place often.	2. Passing through this area my attention is drawn to the green wall.	3. When I am here I pause to observe the details of these green walls.	4. Green walls offer fascinating views of the area.	5. I have curiosity to explore the space I see beyond the green walls (the space offers such stimuli as to activate curiosity and entice exploration).	from work, study, etc.) I choose/ would choose to stand in a spot where I can observe these green walls.	7. I find it relaxing to look at these green walls.	8. The presence of the green walls enhances the feeling of comfort offered by this place.	9. When I am/ if I were on a break (from work, study, etc.), the presence of these green walls gives/ would give me a feeling of mental refreshment	10. In this place, nature takes back its space.	11. Vegetation seems to coexist with the building.	12. Green walls are the defining element of this courtyard.	13. Green walls fits well with the surroundings.	14. The spatial arrangement of this area is well organised.	15. I like that the green walls were included in this courtyard.	16. I like this courtyard.	17. Green walls are my favorite element in this space.
1. I frequent this place often.	1																
2. Passing through this area my attention is drawn to the green wall.	-0,30	1															
3. When I am here I pause to observe the details of these green walls.	-0,30	0,65	1														
4. Green walls offer fascinating views of the area.	-0,18	0,42	0,41	1													
5. I have curiosity to explore the space I see beyond the green walls (the space offers such stimuli as to activate curiosity and entice exploration).	-0,23	0,39	0,65	0,36	1												
6. During a break (from work, study, etc.) I choose/ would choose to stand in a spot where I can observe these green walls.	-0,38	0,43	0,65	0,43	0,61	1											
7. I find it relaxing to look at these green walls.	-0,31	0,43	0,68	0,63	0,62	0,65	1										
8. The presence of the green walls enhances the feeling of comfort offered by this place.	-0,32	0,45	0,46	0,63	0,37	0,42	0,66	1									
9. When I am/ if I were on a break (from work, study, etc.), the presence of these green walls gives/ would give me a feeling of mental refreshment.	-0,36	0,41	0,42	0,55	0,47	0,59	0,61	0,59	1								
10. In this place, nature takes back its space.	-0,17	0,27	0,23	0,32	0,46	0,24	0,25	0,32	0,35	1							
11. Vegetation seems to coexist with the building.	-0,25	0,43	0,32	0,47	0,45	0,33	0,32	0,39	0,48	0,49	1						
12. Green walls are the defining element of this courtyard.	-0,33	0,35	0,35	0,42	0,35	0,36	0,34	0,41	0,48	0,53	0,58	1					
13. Green walls fits well with the surroundings.	-0,11	0,45	0,31	0,45	0,41	0,26	0,34	0,43	0,36	0,47	0,63	0,56	1				
14. The spatial arrangement of this area is well organised.	-0,17	0,30	0,25	0,28	0,31	0,24	0,28	0,30	0,26	0,45	0,41	0,53	0,50	1			
15. I like that the green walls were included in this courtyard.	-0,04	0,40	0,32	0,39	0,37	0,36	0,36	0,50	0,46	0,30	0,45	0,54	0,58	0,48	1		
16. I like this courtyard.	-0,05	0,24	0,10	0,23	0,25	0,25	0,28	0,33	0,34	0,42	0,32	0,35	0,46	0,58	0,44	1	
17. Green walls are my favorite element in this space.	-0,09	0,27	0,32	0,41	0,33	0,35	0,27	0,31	0,44	0,25	0,51	0,59	0,41	0,27	0,42	0,10	1

Table 14. Items' correlations.
Items' Spearman correlations for CAM. Correlations are highlighted in yellow. Item 1 is the only item without correlations.

	1. I frequent this place often.	2. Passing through this area my attention is drawn to the green wall.	3. When I am here I pause to observe the details of these green walls.	4. Green walls offer fascinating views of the area.	5. I have curiosity to explore the space I see beyond the green walls (the space offers such stimuli as to activate curiosity and entice exploration).	6. During a break (from work, study, etc.) I choose/ would choose to stand in a spot where I can observe these green walls.	7. I find it relaxing to look at these green walls.	8. The presence of the green walls enhances the feeling of comfort offered by this place.	9. When I am/ if I were on a break (from work, study, etc.), the presence of these green walls gives/ would give me a feeling of mental refreshment.	10. In this place, nature takes back its space.	11. Vegetation seems to coexist with the building.	12. Green walls are the defining element of this courtyard.	13. Green walls fits well with the surroundings.	14. The spatial arrangement of this area is well organised.	15. I like that the green walls were included in this courtyard.	16. I like this courtyard.	17. Green walls are my favorite element in this space.
1. I frequent this place often.	1																
2. Passing through this area my attention is drawn to the green wall.	0,06	1															
3. When I am here I pause to observe the details of these green walls.	0,14	0,54	1														
4. Green walls offer fascinating views of the area.	0,12	0,46	0,49	1													
5. I have curiosity to explore the space I see beyond the green walls (the space offers such stimuli as to activate curiosity and entice exploration).	0,19	0,31	0,44	0,32	1												
6. During a break (from work, study, etc.) I choose/ would choose to stand in a spot where I can observe these green walls.	-0,10	0,27	0,24	0,28	0,35	1											
7. I find it relaxing to look at these green walls.	0,06	0,48	0,37	0,36	0,28	0,52	1										
8. The presence of the green walls enhances the feeling of comfort offered by this place.	-0,01	0,34	0,35	0,33	0,32	0,37	0,54	1									
9. When I am/ if I were on a break (from work, study, etc.), the presence of these green walls gives/ would give me a feeling of mental refreshment.	0,05	0,39	0,27	0,28	0,23	0,38	0,61	0,45	1								
10. In this place, nature takes back its space.	0,14	0,29	0,38	0,47	0,17	0,26	0,28	0,30	0,25	1							
11. Vegetation seems to coexist with the building.	0,27	0,16	0,28	0,27	0,16	0,13	0,25	0,35	0,29	0,50	1						
12. Green walls are the defining element of this courtyard.	0,04	0,19	0,25	0,34	0,13	0,28	0,22	0,38	0,16	0,34	0,27	1					
13. Green walls fits well with the surroundings.	0,07	0,21	0,30	0,24	0,31	0,27	0,36	0,35	0,44	0,30	0,47	0,26	1				
14. The spatial arrangement of this area is well organised.	0,11	0,31	0,35	0,33	0,18	0,16	0,28	0,31	0,28	0,39	0,44	0,23	0,49	1			
15. I like that the green walls were included in this courtyard.	0,06	0,32	0,23	0,34	0,22	0,21	0,30	0,43	0,45	0,32	0,38	0,13	0,46	0,53	1		
16. I like this courtyard.	0,05	0,30	0,23	0,34	0,10	0,12	0,28	0,33	0,39	0,42	0,48	0,25	0,41	0,57	0,53	1	
17. Green walls are my favorite element in this space.	-0,13	0,40	0,35	0,33	0,15	0,38	0,35	0,38	0,36	0,31	0,16	0,40	0,26	0,20	0,34	0,27	1

Table 15. Items' correlations. Items' Spearman correlations f or CCB. Correlations are highlighted in yellow. Item 1 is the only item without correlations.

ratings than CAM, with the exceptions being item 1, item 2, and item 17. The most significant rating differences between the two sites were observed in item 1, "I frequent this place often" (CAM = 3.78; CCB = 2.82; d = 1.92), item 10, "The green walls fit well with the surroundings" (CAM = X; CCB = X; d = 0.45), item 14, "The spatial arrangement of this area is well organized" (CAM = 3.88; CCB = 4.26; d = 0.38), and item 16, "I like this courtyard" (CAM = 4.01; CCB = 4.35; d = 0.34). Only item 1 (CAM = 3.78; CCB = 2.82), item 2, "Crossing this area, my attention is drawn to the green wall" (CAM = 4.14; CCB = 4.01), and item 17, "The green walls are my favorite element in this space" (CAM = 3.98; CCB = 3.84), received higher ratings in CAM than in CCB.

Item 15, "I like that the green walls were included in this courtyard," received the highest ratings for both CAM (4.39) and CCB (4.53). CAM received higher ratings for item 8, "The presence of the green walls enhances the feeling of comfort offered by this place" (4.29), item 7, "I find it relaxing to look at these green walls," and item 2, "Passing through this area, my attention is drawn to the green wall" (4.15), while lower ratings were received for item 10, "In this place, nature takes back its space," and item 12, "Green walls are the defining elements of this place" (3.54), and item 3, "When I am here, I pause to observe the details of these green walls" (3.55).

On the other hand, CCB received higher ratings for item 7 (4.40), item 8 (4.38), item 13, item 16 (4.35) and item 14 (4.26), while lower ratings were received for item 1 (2.82), item 3 (3.60) and item 12 (3.60).

The Spearman's Ranks Correlation matrices for the five factors and the seventeen items of the Perceived Restorativeness Scale were calculated based on the Likert Scale average evaluations given by all the participants at the CAM and CCB sites. Thus, four Spearman correlations were developed, two for items tested at CAM and CCB, and two for factors tested at CAM and CCB. Concerning the Spearman correlation within items in both sites, the correlations in the questionnaire responses of CAM were more numerous and higher than those in CCB. For a detailed analysis of the results, Table 12 and Table 13 summarize the Spearman correlations of the GwPRS factors while Table 14 and Tablke 15 summarize the Spearman correlations of the GwPRS items in CAM and CCB. Acording to xx, correlations have been considered with a value exceeding 0,40. Values between 0,40 and 0,70 have been considered a moderate correlation, values exceeding 0,70 have been considered a high correlation. It's interesting to note that results from CAM (Table 12) showed very high correlations between Fa and BA (0.70) and EC and P (0.73). Lower correlations were found between Fa and EC (0.59), BA and EC (0.49), P and Fa (0.55), and P and BA (0.59). In contrast, CCB factor correlations appeared quite different (Tab 13). The highest correlation was found between P and EC (0.67), while lower correlations existed between EC and Fa (0.43) and EC and BA (0.51).

4.4 Discussions

Integrating the data gathered through naturalistic observations and the questionnaire enables us to access comprehensive insights into the impact of green walls on spatial perception. These insights are derived from both qualitative and quantitative data. Therefore, the following section combines field observations and information derived from statistical analysis to elucidate the intricate socio-ecological dynamics between individuals, urban environments, and green walls, as outlined by Sutton (2014).

4.4.1 Restorative capacity of green walls in CAM and CCB

Both green walls at the CAM and CCB sites exhibit high average values across all GwPRS factors and a very similar overall GwPRS score. This suggests that, despite the evident differences between the two sites, such as vegetated area size (Timm et al., 2017), accessibility to the green walls (Agnolio et al., 2022), the participant demographic (Teotonio et al., 2020), and space utilization, the influence of the green walls on participants' Perceived Restorativeness is remarkably consistent between the two sites. As Lotfi et al. (2020) had suggested, this initial result indicates the existence of a shared intrinsic Restorativeness value associated with this nature-based solution, as perceived by participants at both sites. It can also be interpreted as an indication of the occurrence of the biophilic process in relation to technological green systems like green walls. This is vital information for urban planning, highlighting the effectiveness of green walls as bio-based technological components that enhance urban livability (Goel et al., 2022).

Examining the pattern of GwPRS responses at both sites, the distribution of answers is quite similar. CCB consistently displays slightly higher values than CAM for all items, with the exception of item 1. However, considering the small differences between the values (except for item 1), there is no substantial distinction in Perceived Restorativeness between the two sites. This suggests that the common characteristics shared by both green walls are the primary drivers of this perceptual process. Consistent with the literature, these characteristics may include their elevated placement on buildings (Perini & Ottelé, 2014), the symmetrical arrangement of green walls that create a multitude of vegetated elements integrated into the urban space design (Terrapin Bright Green, 2021), and the specific type of green wall characterized by a diverse array of visual stimuli due to the variety of plant species (Goncalves et al., 2021).

Notably, both sites exhibit similarities in the results for BA and Fa and EC and P, with high average values and correlations.

This outcome underscores the link between people's aesthetic appreciation of green walls and their perception of comfort and mental relief (associated with the BA and Fa factors). It also underscores the essential role of urban biophilic design in creating a cohesive urban environment that combines natural and artificial elements. This alignment supports the significance of the aesthetic function of green walls as a co-dependent element, a "performative ornament", influencing psycho-physiological reactions (Barbiero et al., 2022). The high BA values in both sites confirm the role of green walls as architectural elements that enhance urban space comfort. Furthermore, the high correlation between EC and P in both sites suggests the importance of planning the integration of green walls as part of landscape design and architectural elements at the building level.
Notably, in CAM the correlation between Fa and BA is quite higher than CCB. For both sites all factors show moderate correlations (0,40-0,70). With very high correlation in CAM between Fa and BA and EC and P (Tables 12 and 13). Moreover, a greater number of correlations in the CAM than in CCB results is also evident when considering the items (Tables 14 and 15). Given the fundamental importance of the BA and expecially Fa factor (Kaplan & Kaplan, 1989), these results are intriguing aspect for further analysis in order to deepen the knowledge to be applied in the green wall design pahse. As a general observation, factor correlations in CAM are higher than factor correlations in CCB.

Exploring the items for which each site received the highest ratings reveals that both CCB and CAM green walls provide a strong sense of comfort and relaxation (item 7 and item 8). For CCB, this may be attributed to the courtyard's layout, its separation from street access, and the quiet atmosphere (Pazzaglia and Tizi, 2022). The positioning of the green wall, covering the entire building height, creates a continuous effect that conveys a sense of refuge (Kellert, 2018). Additionally, close access to the plant species, both visually and physically, fosters an emotional connection with visitors (Hefnawy, 2022). In the case of CAM, being a public open space, the comfort and perspective result from the heights and inclinations of the two green walls, forming a green barrier that surrounds the square and leads to the inner courtyard.

Despite the positive GwPRS values, it is valuable to focus on the main differences between the results of the two sites. Analyzing the factors (Table 12 and 13), it is evident that the F factor at CAM achieves a higher value than CCB, with the most significant difference among all the factors' mean values. The variance is also noteworthy, with CCB showing higher variance than CAM and having the highest variance among all other factors at both sites. Some studies challenge the importance of this factor within the PRS (Hernàndez et al., 2001), but this work recognizes its significance as it provides additional insights into the impact of the green wall on the local community's sense of place. This concept is particularly relevant as it influences the livability of urban spaces (van Dinter et al., 2022). Despite the high total GwPRS values at both sites, the F value at CCB indicates that the overall impact of the sense of place for the community (largely composed of tourists) is low. In contrast, CAM, whose reference community is local, achieves a high average value. This information underscores the importance of considering the sense of familiarity with the analyzed site in the evaluation of the GwPRS.

Based on the results discussed above, demonstrating the impact of green walls on the restorative capacity of an urban space, it is evident that both CAM and CCB spontaneously create gathering and resting points near green walls (Figure 67 and Figure 68). This is practical evidence of the attractiveness of this nature-based solution. Particularly in CCB, visitors have moved their own chairs close to the two living walls to relax and socialize near the vegetation. Notably, in CAM, an aggregation point forms in front of the two green walls where the space is not explicitly designated for gathering or rest. Additionally, there are no benches or free chairs placed in this area. In line with the works of Parker & Simpson (2018) and Peschardt & Stigsdotter (2013) on urban green infrastructure and spaces, this observation serves as empirical evidence of the allure of green walls, influencing behavior in the urban context and creating focal points for people to gather, even where space is not formally designated for such purposes. This outcome suggests that the living walls in CAM are perceived as landmarks.

4.4.2 Improving future investigation

This research reveals that green walls exhibit a high level of Perceived Restorativeness among individuals in two distinct sites, Turin and Lisbon. These results suggest that green walls trigger a biophilic response in people, as evidenced by their capacity to attract individuals to gather in proximity, thereby influencing the utilization of urban space. This finding is of paramount importance and supports the use of green walls as urban tools to enhance the livability of cities.

This research is pioneering in its approach, offering a potential methodological framework to address the current gap in the literature concerning the examination and quantification of the social advantages of green walls in urban settings (Ascione et al., 2020). In this context, the utilization of a well-established tool, the PRS, served as the foundation for the creation of a tailored instrument specifically designed for green walls, allowing research to focus on a recognized and broadly assessed socio-ecological construct.

While the obtained results are highly intriguing, future refinements of the methodology should consider the cultural diversity and subjectivity of questionnaire respondents. The inclusion of open-

ended questions could provide a deeper understanding of individuals' perceptions and the rationale behind their responses. It is advisable to target more homogenous groups of respondents to enable comparative analyses based on shared characteristics among the groups. To gain a more comprehensive understanding of the impacts of green walls, it is essential to extend the observation and questionnaire submission period, encompassing the full range of influences exerted by green walls throughout the year.
Related to this apsect, in order to broaden the knowledge on psychological influence of green walls - and then work on it through their design - the focus of the investigation must be deepened also to possible negative effects that the VGS can have on people's perceptions. In this sense, the perception response to unhealthy state of the vegetation - drought or signs of deseases - or ruined or neglected parts of the system should be inserted and analysed in future studies. The inclusion of these aspect in the analysis will enphasise the crucial role of a well-managed maintenance phase, a commonly recognised critical aspect of the VGSs life cycle.

Given the favorable reliability of the GwPRS, its application in other locations is encouraged, as it could yield further insights into the variables affecting the Restorative capacity of green walls in urban spaces. Systematic data collection could form the foundation of evidence-based biophilic design for green walls and serve as crucial knowledge for policymaking processes in the development of resilient and biophilic cities.
Lastly, the documentation of data related to the cultural ecosystem services of green walls is an essential information source for a comprehensive evaluation of their sustainability in urban environments, including the assessment of their social benefits.

Furthermore, the assessment of intangible benefits remains notably limited, particularly for NBS applications. According to Viti et al. (2022), the prevailing trend in studies concerning the evaluation of social benefits associated with NBS involves the adoption of a *case-specific* approach. This approach, however, presents a challenge as it impedes the replicability of methodologies and the subsequent comparison of results. In contrast, the methodology employed in the present study is intended to facilitate the comparative analysis of green walls across diverse locations. The objective is to establish a framework that can be readily adaptable to various contexts and other instances of NBS. By doing so, this study aims to contribute to the establishment of a standardised and replicable methodology for the assessment and comparison of the social benefits offered by NBS, thereby addressing prevailing limitations within the academic discourse on the subject.

Chapter 5

Conclusions

5.1 In synthesis

In order to easen the comunication of the research results, keyfindings are listed below.

5.1.1 On alternatives growing media

The work of reserach presented in Chaper 3 can be summarysed in the following takeaways:

Performance of Alternative Growing Media
- Hazelnut shells-based and cork-based growing media showed better performance over traditional potting soil for *C. comosum* and *S. wallisii*.
- Hemp stalks-based growing medium showed advantages, not requiring pre-treatment before its incorporation into potting soil.

Characteristics of Alternative Growing Media:
- All alternative growing media showed favorable characteristics such as volume stability, lightweight and lower water consumption compared to potting soil.
- These properties make them compelling choices for creating lightweight, durable and low water-demanding VGS.

Recommendations for Further Studies:
- Testing varied material mix percentages is incouraged to understand optimal combinations.
- Calls for comprehensive chemical and biological assessments to gain a deeper understanding of alternative growing media characteristics.
- Need for additional data analysis and

testing to enhance and expand the reults.

Broader Characterization and Evaluation:
- A broader characterization of innovative organic growing media, including physical, chemical and biological tests is suggested.
- Prioritise the assessment of nutritional values and chemical properties to design suitable fertigation strategies.

Circular Bioeconomy and Sustainable Design:
- Highlights the potential of reuse bio-resources to establish a local circular bioeconomy for VGSs.
- Stimulates innovative advancements in VGSs, especially in regions where the studied bio-resources are readily available.

Multi-Criteria Matrix and Methodology:
- Presents a baseline for a multi-criteria matrix as a foundational tool for the selection of alternative growing media, suggesting its further development.
- Recommends incorporating additional properties and growing media characteristics into the matrix.

The experiment encourages the application of the methodology in various geographical contexts, fostering collaboration between academics and practitioners.
Furthermore the work paves the way for the collection of pivotal information for the investigation of growing media. Indeed, the study calls for conducting an environmental life cycle assessment for each growing medium to provide a comprehensive understanding of strategies to enhance the sustainability of VGSs design.
The experiment emphasizes the potential of alternative growing media for VGSs, underscores the importance of comprehensive assessments and further studies and advocates for a sustainable and circular approach in designing and implementing these systems.

5.1.2 On the perception of green walls

The results of Chapter 4 can be summarised according to the following points:

Perception of the restorative capacity of green walls:
- Green walls are associated with a high level of perception of restorative capacity among individuals in Turin and Lisbon.
- Green walls trigger a biophilic response, attracting people to congregate in close proximity and influencing the use of urban space.
- According to the results, green walls can be conceived as urban tools to improve the liveability of cities.

Pioneering methodological framework:
- Need to examine and quantify the social benefits of green walls in urban settings, filling a gap in the existing literature.
- Define a green wall social benefits assessment method as a tool for assessing the well-being of individuals, adapting the Restorativeness Perception Scale (PRS)

Application of the GwPRS in other locations:
- Encourages the application of the Green Wall Restorativeness Perception Scale (GwPRS) in other locations to gain further insights into the variables that influence the restorative capacity of green walls in urban spaces.
- Systematic data collection as a basis for examining and quantifying the social benefits of green walls in urban settings, filling the gap in the existing literature.
- Systematic data collection as a basis for evidence-based biophilic design for green walls and as crucial knowledge for policy-making processes for the development of resilient, biophilic cities.

Documentation of cultural ecosystem services:
- The study emphasises the importance of documenting data on the cultural ecosystem services of green walls as under-investigated aspects of urban processes.
- This information is essential for the management of cities.

5.2 Outcomes : a common perspective

The present doctoral dissertation consists of two separate studies, each related to different research areas. Despite the different subject matters, there is a noticeable convergence in the methods and perspectives used in both studies. This strong alignment defines a comprehensive framework and perspective characterising the doctoral dissertation. The developed approach focused on data-driven and evidence-based design highlights the integrative strength and coherence of the overall scholarly effort, reinforcing its significance within the academic community.

5.2.1 Sharing tools and methodologies

The results of the studies highlight the crucial importance of a careful design approach in the implementation of VGSs, which takes into account the specific characteristics of the context in which these systems are applied. The sustainability and intangible benefits of these systems are closely linked to the unique circumstances of their application, emphasising that a general approach is insufficient. The findings confirm the crucial importance of adopting a multidisciplinary approach in the design of VGSs, extending its relevance to nature-based solutions more broadly. Furthermore, the research emphasises the need to adapt research and design methodologies to address the complexity of nature-based solutions and the evolving contemporary cities. Two key aspects, namely the system sustainability and the social benefit assessment, require more inclusive consideration within academic discourse and practical application. Practical methodological paths of investigation and evaluation have been proposed for both aspects. Recognising the challenge of reproducibility in nature-based solution planning and design, the proposed methodologies and tools aim to facilitate the acquisition of case-specific information and data, useful to guide the design phase. Infact, both studies highlight the imperative of generating and aquire project-oriented data and information, which are essential to guide the sustainable evolution of vertical green systems. In this way, VGSs can be fundamental strategic solutions for advancing Biophilic cities. The collection and analysis of project-specific data offer valuable insights into the effectiveness and impact of VGSs or nature-based solutions, informing future design decisions and policy formulations for sustainable urban development.

The employed methods and methodologies actively promote the formulation and refinement of these protocols within multidisciplinary research sectors and groups. The project-oriented nature inherent in these methodologies is meant as effective strategy towards the practical application of the obtained results. Anchored in the concept of the "city as a laboratory", the research conducted in this thesis on the sustainable innovation of VGSs can be adapted and implemented for bottom-up practices of involvement and experimentation within the Biophilic city framework. This adaptability can give rise to living labs or citizen science initiatives guided by the lens of Urban ecology, paving the way for widespread and sustainable application of vertical greenery.

5.2.2 Project-oriented reserach

The results of both studies provide valuable insights into the adoption of an approach to design research that prioritises the systematic gathering of information, acting as a driving force for a scientifically based design process. Design, which operates both deductively and creatively, seamlessly incorporates a scientific approach, using research as a central tool to explore and address complex issues. Within this conceptual framework, design is a mode of enquiry that structures research activities to acquire information that is indispensable for the definition of the nature-based solution. This design research approach, based on the systematic collection of information, supports an integrative design paradigm that places data at the centre of design. Through this approach, information is a dynamic catalyst for multi-scalar application, particularly in the context of vertical green systems and nature-based solutions.

The development of this approach involves the implementation of protocols, laboratory tests and surveys, highlighting a dedicated commitment to accuracy and measurability during the early stages of the design process. The scientific methodology employed produces both tangible and intangible results in a qualitative and quantitative manner, creating a solid repository of data that serves as the basis for subsequent decisions and iterations.Innovating in the design of VGSs - and the application of nature-based solutions - necessarily required a scientific approach that captures both quantitative and qualitative data.

5.2.3 The importance of evidences

VGSs can play a central role in reshaping the built environment and improving liveability. As design becomes an active enquiry, the importance of informed decision-making through systematic data collection becomes increasingly significant. The complexity of functions and benefits of VGSs highlight the importance of adopting locally informed production, design and decision-making practices rooted in empirical evidence. Within this perspective, data-driven and evidence-based biophilic design becomes a comprehensive approach that aligns with the multiple demands of contemporary urban landscapes.
Based on this, this thesis demonstrates empirical evidence of the positive outcomes of designing VGSs for environmental and social sustainability. The integration of a rigorous, data-driven and evidence-based design approach for the implementation of VGSs responds not only to aesthetic considerations, but also to the broader current goals of sustainability and improved quality of urban life. Greening the city envelope is no longer limited to a superficial aesthetical improvement of urban spaces, but address the complex challenges of modern urban life. The iterative and evidence-based nature of design research ensures that each innovation is purposeful, contributing not only to the immediate visual appeal, but also to the ecological health and long-term functionality of urban ecosystems.

The systematic gathering of information through protocols, laboratory tests and surveys becomes a fundamental practice in shaping sustainable solutions. This meticulous approach recognises the intricate relationships between ecological processes, social dynamics and design choices. Sustainable innovation in VGSs, based on empirical evidence becomes a multifaceted intervention that provides ecological services, increases biodiversity, mitigates heat islands and improves air quality. These tangible benefits, harmonised with aesthetic considerations, create a symbiotic relationship between the built environment and nature, fostering visually pleasing and ecologically resilient urban spaces.

The central role played by VGSs gains importance in the face of wider urban challenges. The expansion of cities requires not only innovative design solutions, but also a paradigm shift towards sustainability. From a socio-ecological perspective, the dynamic nature of sustainable design responds to the evolving challenges posed by urbanisation.

It extends beyond environmental considerations to include social, economic and cultural dimensions. Sustainable innovation emerges as a catalyst for the creation of urban environments that are not only ecologically resilient, but also socially inclusive and economically sustainable. The synthesis of the design research approach and sustainable innovation in VGSs emphasises the need for holistic urban design. This data-driven and evidence-based approach enriches the field of design research and can concretely support the creation of sustainable, resilient and harmoniously nature integrated urban landscapes.

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Chapter 4

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