sustainability

MDPI

Article

Deepening Layers of Urban Space: A Scenario-Based Approach with Artificial Intelligence for the Effective and Sustainable Use of Underground Parking Structures

Başak Aytatlı [1], Selcan Bayram [2] and Semiha İsmailoğlu [3,*]

[1] Department of Landscape Architecture, Faculty of Architecture and Design, Atatürk University, 25120 Erzurum, Türkiye; basakaytatli@atauni.edu.tr
[2] Department of Urban and Regional Planning, Faculty of Engineering and Architecture, Yozgat Bozok University, 66100 Yozgat, Türkiye; selcan.bayram@yobu.edu.tr
[3] Department of Architecture, Faculty of Engineering and Architecture, Recep Tayyip Erdogan University, 53100 Rize, Türkiye
* Correspondence: semiha.ismailoglu@erdogan.edu.tr

Abstract

This study proposes a scenario-based conceptual model for transforming underground parking structures into sustainable interior green spaces, directly addressing two core research dimensions: energy efficiency and user experience. The originality of the research lies in repositioning subterranean spaces—often overlooked in urban planning—as climate-responsive, multi-functional public environments. Using a site-specific case in downtown Rize, Türkiye, three design scenarios—passive green walls, active modular systems, and experimental micro-farming—were comparatively analyzed. These scenarios were assessed through AI-assisted simulations and climate-based performance evaluations in terms of environmental benefits, thermal regulation, carbon reduction, and experiential quality. Underground space leads to green design interventions, which in turn generate environmental, energy, and social benefits. The results demonstrate that passive systems provide cost-effective improvements, active modular systems achieve balanced performance, and experimental micro-farming yields the highest ecological and social benefits. The study uniquely contributes to urban sustainable design by integrating climate-adaptive strategies, biophilic design principles, and AI-supported visualization into the transformation of underground structures. This research not only advances academic discourse but also provides policy-relevant insights for local governments, developers, and communities in the context of urban renewal.

Keywords: sustainability; underground structures; landscape; indoor landscaping; vertical garden; artificial intelligence supported landscaping

check for updates

Academic Editors: Alejandro Rescia and Giouli Mihalakakou

Received: 22 July 2025
Revised: 17 October 2025
Accepted: 18 October 2025
Published: 22 October 2025

Citation: Aytatlı, B.; Bayram, S.; İsmailoğlu, S. Deepening Layers of Urban Space: A Scenario-Based Approach with Artificial Intelligence for the Effective and Sustainable Use of Underground Parking Structures. *Sustainability* **2025**, *17*, 9397. https://doi.org/10.3390/su17219397

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Global urbanization dynamics have profoundly reshaped the spatial relationship between humans and nature over the past decade. Increasing population density, urban expansion, and the reduction in natural areas have elevated sustainability to a central concern in urban planning and design. Contemporary urban life, extending beyond basic functions such as housing and transport, now directly influences individual physical and psychological well-being [1]. Consequently, cities must be understood not only through their built environments but also through their integration with natural systems—an area

of growing importance for ecological and social sustainability. Reports from the United Nations and UN-Habitat highlight that limited access to green spaces leads to declining quality of life, rising climate inequalities, and loss of ecosystem services [1,2]. Although protecting and planning open green spaces remain key objectives of sustainable urban policy, these goals are increasingly challenged by urban density, high land values, and shifting investment priorities [3].

To address this, strategies such as interior landscaping, vertical gardens, green roofs, and micro-landscape systems have emerged to reintegrate nature into cities. However, while these approaches primarily focus on surface areas, extensive underground structures remain underexplored within landscape architecture and urban design. Urban development inherently forms a multilayered system above and below ground, each presenting unique opportunities and constraints. Whereas surface spaces offer openness and spontaneity, underground environments—though enclosed and controlled—are not disconnected from nature; air, water, and vegetation can exist where sufficient light is available. Thus, underground structures accessible from multiple levels or located beneath flat urban areas possess the potential to create new spatial layers and depths, redefining them as active components of sustainable urban form rather than isolated buried spaces [4–7].

Although above ground and underground spaces differ in form and perception, both aim to meet human needs. The integration of natural elements into interior environments has been widely studied for their restorative potential and behavioral influence. Nature-based design promotes cognitive restoration and stress reduction by enhancing perceptions of restorativeness and connectedness with natural systems [8,9]. Meta-analyses confirm that natural environments consistently outperform urban settings in generating restorative experiences [10], while contact with nature fosters pro-environmental and prosocial behaviors that shape attitudes toward biodiversity and conservation [11]. Even simulated or virtual nature experiences can elicit similar positive responses [12]. Thus, embedding nature within underground interiors extends beyond aesthetics and ecology, enhancing well-being and encouraging sustainable behavioral patterns.

A livable space requires essential qualities such as orientation, light, ventilation, and acoustics. While surface structures often acquire these attributes naturally, poor planning can lead to issues like congestion and reduced quality of life. Conversely, underground spaces—such as metro stations, parking garages, and pedestrian passages—hold potential as adaptable public environments but are often underused due to negative perceptions. Redesigning these spaces according to user expectations, spatial comfort, and environmental sustainability principles is therefore essential [13,14]. Comprehensive evaluation of underground areas can facilitate the relocation of urban functions below ground, creating new open and green spaces and enhancing overall livability [15,16]. Integrating greenery into underground structures further adds ecological, social, and aesthetic value, strengthens human–nature connections, and promotes micro-scale sustainability in urban contexts [17–20]. This study addresses the dual challenge of enhancing both the environmental performance and experiential quality of subterranean spaces. Integrating scenario-based modeling with biophilic design principles, it establishes a conceptual framework that links energy efficiency with the psychological and social dimensions of underground adaptive reuse. The approach emphasizes the synergy between environmental optimization and user-centered design—an intersection rarely explored in underground spatial transformation. This perspective aligns with the "experience–performance nexus" proposed by Steemers (2003) and Ulrich (1984), which views energy efficiency and human well-being as interdependent goals of sustainable architecture [21,22].

The study was conducted using AI-supported simulations in line with landscape architecture and interior design principles. Design scenarios were visualized with tools

such as Microsoft Designer, OpenAI DALL·E 3, and Artguru v2.0, and analyzed for planting patterns, interior material textures, spatial configurations, and energy performance parameters, reflecting current approaches to integrating AI-generated content (AIGC) in landscape and interior design [23–25]. The research investigates the potential of microecosystems specifically designed for underground parking structures to transform them into next-generation public spaces that contribute to urban natural cycles while generating aesthetic, social, and ecological value. Proposed designs include multi-layered spatial solutions that enhance the user experience, support environmental sustainability, and integrate both ecological and aesthetic functionality. Functionally diversified public space proposals aim to maximize the social and cultural benefits of underground areas, emphasizing their role beyond infrastructure to enrich urban life. By combining environmental performance assessment with considerations of human experience, the study offers a holistic approach to transforming underground spaces into sustainable, nature-inspired urban interiors.

1.1. Indoor Parking Lots and Sustainability

Sustainable urbanization entails not only the creation of new building areas but also the reassessment of existing structures in environmental, social, and economic contexts [26]. In this regard, transforming indoor parking lots into sustainable interior spaces has gained growing theoretical and practical significance. Increasing vehicle ownership and parking demand reveal that single-function, user-unfriendly, and environmentally insensitive designs contradict sustainability principles [27–29]. Converting these structures into multifunctional, environmentally responsive, and socially engaging spaces is thus central to sustainable urban transformation. Such interventions enhance spatial efficiency, optimize resource use, reduce environmental impacts, and improve urban life quality. Adaptive reuse within sustainable urbanization policies extends beyond physical renewal to encompass spatial identity reconstruction, support for ecological cycles, and the reshaping of social relations [30]. Consequently, transforming parking structures into sustainable interiors represents a new mode of spatial production that minimizes resource consumption, fosters social interaction, and emphasizes that sustainable urban development depends on generating new urban dynamics through existing building stock [31–33].

The concept of sustainable interior design incorporates multidimensional criteria such as resource efficiency, environmentally responsible material use, and user health and comfort. Technologies developed within this framework aim to maintain ecological balance while enhancing living environments [34]. In the transformation of indoor parking garages, energy efficiency and environmentally compatible approaches are critical determinants. Research on sustainable architecture and thermal performance underscores the necessity of employing energy-efficient strategies and technologies in adapting existing structures [22,35,36]. Accordingly, the integration of energy-efficient systems, natural lighting and ventilation, sustainable material selection, and waste management constitutes a key framework for achieving sustainability in such transformations.

In urban transformation projects, the principle of sustainability should be considered not only in the design of new buildings but also in the reuse of existing structures. It is emphasized that transformation projects in Turkey are often limited to the physical dimension, whereas socio-economic and cultural aspects should also be considered [19]. In this context, the transformation of indoor parking lots into sustainable interior spaces reflects a multi-dimensional approach. Repurposing defunct parking lots in city centers to meet social needs will improve the quality of urban life. Blurring the boundaries between public and urban interior spaces and creating layered spatial experiences in multifunctional transformation projects is being discussed [37]; such relationships will enhance the user experience in parking lot transformations and support spatial sustainability.

It is stated that technologies and products developed within the scope of sustainable architecture support the effective and efficient use of natural resources throughout the life cycle of buildings [34]. In the transformation of indoor parking garages, the use of such technologies and products will both reduce energy consumption and minimize environmental impact [38]. Furthermore, studies on operational energy savings highlight the necessity of using energy-efficient strategies and technologies in the transformation of existing buildings [36]. In this context, elements such as the integration of energy-efficient systems, the implementation of natural lighting and ventilation solutions, sustainable material selection, and waste management are prominent in the process of transforming indoor parking garages into ecologically functional interior spaces [39–41]. Transforming public spaces and urban interiors is a crucial aspect of sustainable urbanization. The Helsinki example illustrates how integrating public interiors with the urban landscape through multifunctional projects supports sustainable urban and cultural development. The Lasipalatsi Square and Amos Rex Underground Museum exemplify this interior–exterior continuity within the framework of sustainable urban transformation (Figure 1) [37].

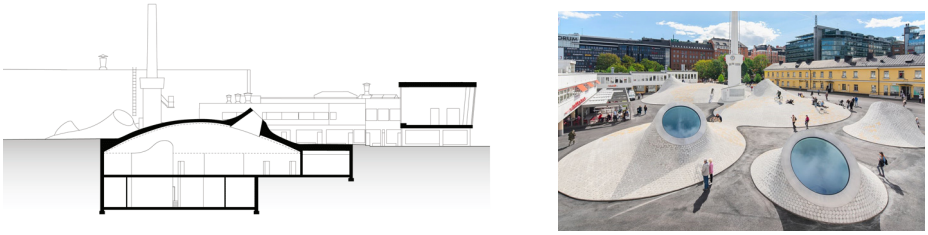


Figure 1. Helsinki's Lasipalatsi Square and the Amos Rex Underground Museum [42,43].

This example demonstrates that parking garages can be transformed into sustainable interior spaces serving public functions. Multifunctional transformation projects emphasize blurring the boundaries between public and urban interiors and fostering layered spatial experiences, which enhance user engagement and support spatial sustainability [1,36,44]. During this transformation, criteria such as resource efficiency, natural resource management, waste reduction, and user health should be prioritized alongside social needs. Technologies developed within sustainable architecture frameworks promote efficient resource use throughout a building's life cycle [34]; their integration into parking garage transformations reduces energy consumption and minimizes environmental impacts.

1.2. Indoor Parking Lots and Green Areas

Transforming underground structures into climate-adaptive green interiors presents an innovative strategy for addressing the dual challenges of urbanization and environmental sustainability. Grounded in biophilic design principles, this approach seeks to strengthen the human–nature connection within urban settings. Nature-integrated design extends beyond the mere addition of greenery; it represents a holistic framework that embeds natural elements into architecture and urban planning to minimize ecological footprints while enhancing psychological and physiological well-being [45,46]. Despite infrastructural expansion in the 21st century, the neglect of natural environments has created significant urban challenges [47]. As societies grow increasingly detached from nature, reintroducing natural features into urban spaces has become essential. Studies demonstrate that integrating trees, gardens, and natural habitats enhances urban biodiversity and contributes to residents' mental health and overall well-being [16,31,48].

A critical aspect of transforming underground spaces lies in effectively integrating light, greenery, and natural forms to evoke biophilic responses. Studies show that environments incorporating natural materials, daylight, and nature views significantly reduce

stress and enhance mood [32,49]. Indoor gardens and living walls serve not only aesthetic purposes but also function as therapeutic elements that improve occupant health and productivity [33,50]. Reimagining underground spaces—often built for purely functional uses and neglected over time—as green interiors can help urban residents reconnect with nature and foster well-being and social cohesion [45,51]. Given that these areas are major sources of environmental burden due to vehicle-induced carbon emissions and air pollution [52,53], integrating energy-efficient systems with greening strategies yields multiple benefits, including improved air quality, moderated microclimates, and enhanced water management [54,55]. Green infrastructure thus plays a vital role in improving the environmental performance of subterranean interiors where natural elements are scarce [45,56].

Moreover, enhanced access to nature has been shown to increase social interaction and overall quality of life [57,58]. Sustainability in underground interior planning should therefore encompass not only energy performance but also ecological resilience. The use of native plants supports self-sustaining, low-maintenance landscapes, while rainwater harvesting systems can create habitats that benefit both people and local wildlife, reinforcing urban biodiversity—a core tenet of biophilic urbanism [14,15,59]. Ultimately, biophilic transformation of underground structures, through restorative design and sensory integration, offers a pathway to healthier, more resilient urban environments that mitigate the stresses of dense city living and promote long-term well-being [60,61].

1.3. Research Questions

Considering the environmental burden posed by underground car parks and the growing interest in their ecological and social renewal through greening strategies, it is essential to investigate not only the environmental outcomes of such transformations but also their impact on user experience and urban life. The research adopts a dual focus: Optimizing the environmental performance of underground spaces through biophilic and passive design strategies, and Enhancing user experience via perceptual comfort, biophilic engagement, and social usability. This dual structure forms the conceptual backbone of the study. Accordingly, the research is guided by the following questions:

1. How do green infrastructure interventions in underground parking structures affect environmental outcomes such as air quality, energy efficiency, and microclimatic regulation?
2. How do these interventions affect user comfort, perceptual experience, and psychological well-being?

2. Literature Review

The integration of green infrastructure in urban environments has long been recognized for its ecological and social benefits. Im (2019) highlights that urban greening interventions such as green streets and parks effectively mitigate heat island effects, improve air quality, and support stormwater management [62]. Onishi et al. (2010) demonstrated that converting surface parking lots into vegetated areas significantly reduced localized surface temperatures by up to 5–7 °C [63]. However, as cities become denser, attention shifts toward underground spaces, which present unique environmental challenges. Underground parking garages contribute notably to urban pollution due to carbon emissions and poor ventilation [52,64]. On the other hand, Cao et al. (2022) show that green technologies, such as light guide systems in subterranean infrastructure, can substantially reduce electric lighting demands, promoting performance improvements and ecological integration [65]. Additionally, field experiments by Kondo et al. (2000) demonstrated that installing high-velocity fan-diffuser units in underground parking garages significantly improves ventilation efficiency by reducing the age of air, which has positive implications

for both air quality and thermal comfort [66]. This finding underscores the value of design interventions targeting pollutant removal and indoor environmental improvements in subterranean public facilities. Regarding user experience, Novalia et al. (2024) found that green roofs installed above underground structures significantly enhance perceptual comfort, with visual comfort being especially important for users relocated from surface to subterranean environments [67].

Transforming underground parking structures into sustainable interior environments requires a multidimensional understanding of green infrastructure performance, encompassing climatic compatibility, energy efficiency, user well-being, and ecological impact. Research shows that green wall systems enhance both functional and aesthetic qualities; Akkan Çavdar (2025) found that applying green walls to a sports hall façade reduced annual heating loads by 6.84% and carbon emissions by 4.54%. Broader studies report that such systems can lower urban temperatures by up to 31 °C and absorb over 80% of noise pollution [68]. AI-assisted simulations further enable effective visualization and assessment of these strategies. Collectively, these findings demonstrate that green walls significantly improve ecological, thermal, and experiential aspects of urban spaces. Applied to underground parking transformations, they can elevate environmental quality and user experience. Similarly, Vaverková et al. (2024) show that both intensive and extensive green roofs on underground garages yield positive environmental, social, and economic outcomes, supporting comprehensive sustainability goals [69].

Theoretical Framework: From Underground Space to Green Design Outcomes

The theoretical framework developed in this study conceptualizes the transformation of underground parking structures as a systemic process in which the latent capacities of subterranean space are activated through targeted green design interventions, producing measurable environmental, energy, and social benefits. Interventions such as daylight integration, vegetated envelopes, passive ventilation, and modular planting mediate thermal behavior, resource flows, and perceptual qualities; improved environmental performance and enriched user experience thus form a mutually reinforcing nexus that guides the scenario-based comparative analysis. This integrative framing draws on theories of adaptive reuse, urban metabolism, and biophilic urbanism [70–72] and provides the logical scaffold for linking specific design choices to both performance metrics and experiential outcomes.

3. Materials and Methods

3.1. Materials

This study proposes a conceptual design model for transforming underground structures into indoor landscape areas to meet the need for sustainable urban green spaces. The underground parking garage used as a sample in this study is in the city center of Rize, in the Black Sea Region of Turkey, near the Faculty of Theology at Recep Tayyip Erdoğan University (41.0373° N, 40.4972° E). Due to its location, which is both a busy pedestrian area and a hub for academic and social activities, it also represents high value for green transformation in terms of user experience and social interaction (Figure 2). The region exhibits the typical characteristics of the Black Sea climate, characterized by high humidity and heavy rainfall throughout the year. The average annual rainfall exceeds 2000 mm, and precipitation is frequent and heavy, especially in autumn and winter. These humid and cool climatic conditions support the lush vegetation throughout the year, but they also increase the humidity load on buildings and require attention to air circulation. The parking lot has a total of approximately 822 m^2 of vertical wall surface on all four sides. Different green wall systems that could be applied to all these surfaces were compared on a scenario

basis. Designs and scenarios were created in line with the data produced by the software. Designs suitable for the interior spaces of underground parking garages in the city center were proposed.

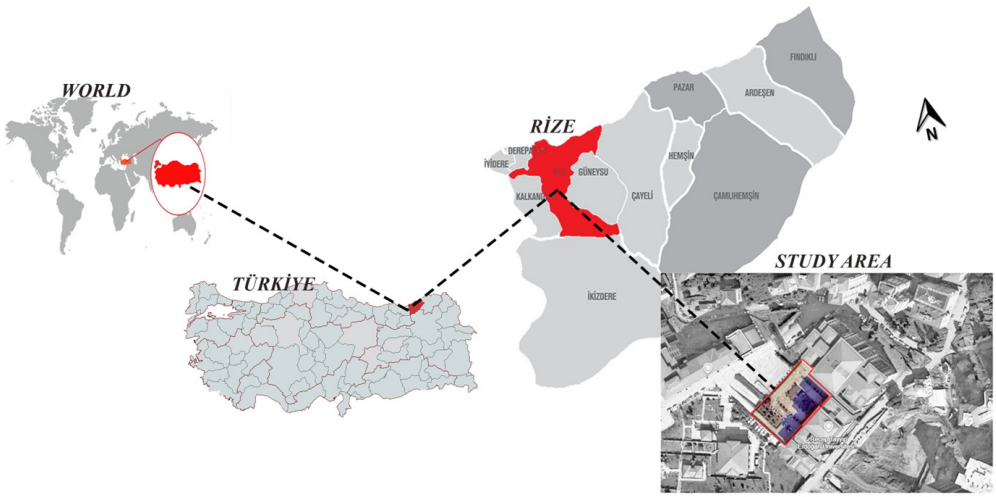


Figure 2. Location Map of Rize [Created by authors].

3.2. Methods

This research, conducted within the framework of qualitative research methods, adopts a holistic methodological approach that combines literature review, theoretical framework development, artificial intelligence-assisted visualization, and spatial simulation processes using computer-aided design tools. The primary objective of the study is to develop a scenario-based conceptual design model for the transformation of underground structures into sustainable indoor green spaces. To this end, the theoretical basis was established by reviewing national and international literature on sustainable interior design, biophilic and biomimicry-based approaches, underground structure reuse, and nature-based solutions [73]. Existing indoor parking structures in the city center of Rize were selected as the study area for applied design analyses. These areas were evaluated in terms of their physical accessibility, structural suitability, and transformation potential, and served as a sample for simulation applications. The underground parking lot transformation design proposed in this study was evaluated not only from an architectural perspective but also in terms of energy efficiency and user well-being based on local climate data. For this purpose, psychrometric analyses, light level criteria, and passive design strategy inferences were conducted using hourly climate data for Rize province using Climate Consultant 6.0 software (Build 17, UCLA Energy Design Tools, Los Angeles, CA, USA), based on the Rize (RI) TMYx 2009–2023 dataset obtained from the Turkish State Meteorological Service (Ankara, Türkiye). These climatic data were not employed for full-scale dynamic energy simulations, but rather as decision-support inputs to define the local environmental context and to guide passive/active design strategies. Specifically, they informed the selection of plant species, building envelope strategies, lighting systems, and ventilation models, ensuring that the AI-assisted design remained climatically responsive and performance-oriented [74,75]. The design process was conducted using AI-powered tools such as Microsoft Designer, OpenAI DALL·E 3, and Artguru v2.0. These tools visualized different scenarios in terms of planting patterns, interior atmosphere, user orientation, and spatial functionality. The visuals allowed for the evaluation of the user experience within the framework of interaction with nature. During this process, natural light transmission, ventilation mechanisms, plant layout schemes, and the integration of ecosystem components into space were tested in digital environments. Finally, all visual and spa-

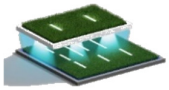
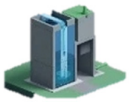
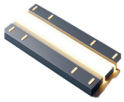
tial outputs obtained during the data analysis process were evaluated using qualitative content analysis. The proposed design scenarios were comparatively analyzed in terms of aesthetic integrity, ecological functionality, spatial livability, and urban contribution. This comparative analysis was carried out by the research team, consisting of landscape architects, an interior architect, and an urban planner, drawing on their respective expertise in ecological performance, energy and comfort parameters, and spatial quality. The evaluation was guided by criteria synthesized from established frameworks in the literature, including LEED (Leadership in Energy and Environmental Design) and WELL Building Standards, as well as restorative environmental design principles. Accordingly, each design scenario was reviewed in terms of aesthetic integrity, ecological functionality, environmental comfort, and urban contribution. This approach ensured that the analysis was both literature-based and discipline-informed, providing a multi-perspective assessment of the proposed transformations. All simulations and graphical analyses generated in Climate Consultant 6.0 are based on the Typical Meteorological Year (TMYx) file for Rize, Turkey (2009–2023). The dataset was compiled from the ERA5 and NCEI ISD reanalysis archives and represents a 15-year period of hourly climate records. This composite dataset provides statistically typical conditions for energy and environmental performance modeling in the study area. Simulation outputs generated in Climate Consultant 6.0 were evaluated against simplified thermal balance models and empirical benchmarks reported in comparable underground-space studies [63]. Parameters used in the AI-assisted design process such as daylight levels, ventilation rates, planting density, and material reflectivity were calibrated based on literature values and real-world precedents. This multi-step validation ensured the consistency of simulation-derived environmental indicators with physical and experiential conditions observed in subterranean environments. These analyses enabled the understanding of the multi-layered contributions of design components to urban life and their optimization according to sustainability criteria.

During the modeling phase components such as vertical gardens, green walls, modular plant units, domes providing natural light transmission, energy-efficient lighting systems, artificial ponds, misting systems, and biofilters were designed in the digital environment. The functional roles and technological features of these components are comprehensively discussed to support environmental sustainability as well as their aesthetic contributions (Table 1).

Table 1. Nature-integrated Design Components in Underground Areas.

Ikon	Design Component	Description	Technological Infrastructure	Functional Role/ Area of Use
	Vertical Gardens	Planted vertical panels integrated into the interior surfaces of the building	Automatic irrigation, root sensors, photosynthetic LED systems	Improves air quality, provides visual integrity, enhances the biophilic experience
	Green Walls	Plant tissue attached to the wall with artificial or natural support systems	Moisture sensors, drip irrigation systems	Contributes to thermal insulation, sound absorption and visual aesthetics

Table 1. *Cont.*

Ikon	Design Component	Description	Technological Infrastructure	Functional Role/ Area of Use
	Plant Module	Portable and interchangeable plant containers	Self-watering containers, humidity control sensors	Flexible design, adaptability to seasonal change, ease of maintenance
	Floor Lighting	Low energy consumption light systems integrated into walkways	LED light bands, motion sensors	Routing, security, night use
	Greywater Recycling System	Treatment and reuse of wastewater for irrigation purposes	Gray water recovery, smart irrigation systems	Saves water, creates sustainable cycle
	Hydroponic Module	Vertical or horizontal plant systems working with hydroponics	Nutrient solution pumping systems, automatic light/water balance	Space savings, controlled production and low maintenance
	Natural Light Dome	Domed openings or fiber tubes that transmit light through the surface	Light tubes, glass floor panels	Allows sunlight to reach underground, reducing energy consumption
	Urban Seating Unit	Seating elements integrated into the structure, integrated with nature	Acoustic panels, modular furniture	Provides spaces for social interaction and allows users to relax
	Guiding LED Strip	Linear light elements embedded in the ground	LED strips, timers, motion sensors	Strengthens orientation, security and spatial perception

Plant material selection was carried out in accordance with specific criteria, considering the limited natural light and air circulation conditions of underground spaces, and differing from conventional landscaping approaches. Shade-tolerant epiphytes, ferns, succulents, ivy species, and hydroponic plants, which are suitable for low-light tolerance, humidity requirements, root development, and maintenance requirements, were selected. The selected species were integrated into space in accordance with biophilic design principles, supported by artificial lighting systems such as photosynthetic LED lighting. This aimed to improve air quality, promote psychological comfort, and enhance spatial aesthetics. Furthermore, within the scope of nature-inspired design strategies, channel systems based on the passive ventilation logic of termite nests and modular landscape solutions referencing the structural characteristics of fungal mycelial networks were developed and functionally integrated into the design (Table 2).

Table 2. Types of Plant Materials, Ecological Requirements and Purposes of Use in Underground Car Parks.

Vegetable Material/Species Group	Area of Use/Purpose	Ecological Demand	Placement Format	Rationale for Eligibility
Shade-Tolerant Indoor Plants	Improving air quality, creating a biophilic effect	Low light, moderate humidity, low maintenance	Planters, modular vertical wall panels	Able to photosynthesize in low light, providing visually dense leaf texture
Epiphytic Plants	Aesthetic and artistic accent on wall and ceiling surfaces	Ambient humidity is sufficient, no soil needed	Hanging systems, glued natural surfaces	Can survive hydroponics, used on top surfaces with the advantage of low weight
Moss Panels/Moss Walls	Acoustic insulation, aesthetics, creating a natural atmosphere in the interior	High humidity, constant temperature, low light	Vertical surface modules	No irrigation, low biological maintenance, sound absorbing
Hydroponic Plant Systems	Production in a controlled environment, sustainable food production	Support with nutrient solution, artificial light requirement	Raised systems, vertical agricultural walls	Hydroponic production possible, enabling integration of urban agriculture
Bioluminescent Plants/Fungi	Natural lighting, atmosphere creation	Controlled temperature, humid environment	Vertical surfaces, niche areas	Provides light production, aesthetic and experiential value
Creeping Groundcovers	Soft transitions on the ground, natural landscape effect	Humid environment, low light	Micro-elevations, ecological islands	Creates a natural surface effect, covers the soil, low maintenance
Dwarf Species of Bamboo/C. Lucky Bamboo	Modular plant areas, creating a focal point	Medium light, constant humidity, can be supplemented with artificial light	Large pot groupings, linear placement	Provides structural uprightness, directs light upwards
Fern Species (Ferns)	Filtering toxins in the air, balancing humidity	High humidity, shade, good drainage	Wall systems, modular surfaces	Contributes to indoor air quality, provides visually full green texture

In this phase, three alternative design scenarios were formulated to represent different levels of technological integration and ecological contribution:

(1) *Passive Green Walls*, which utilize soil-based or hydroponic vertical planting systems to enhance interior air quality and aesthetics with minimal technological input;
(2) *Active Modular Plant Systems*, which employ hydroponics, automated irrigation, and artificial lighting to optimize resource efficiency and user comfort under controlled conditions; and

(3) *Experimental Micro-Farming Units*, which explore productive uses of underground interiors through small-scale cultivation systems integrating water recycling and LED-based photosynthesis support.

These scenarios provided the comparative framework for subsequent evaluation of ecological functionality, occupant well-being, and urban contribution.

4. Results

In this study, design scenarios developed for the re-functionalization of underground parking lots were evaluated in terms of climatic suitability and thermal performance. The extent to which the proposed strategies align with regional climatic conditions was analyzed using the "Adaptive Comfort"–based annual design guide generated for Rize Province through Climate Consultant 6.0. Digital simulations were conducted in parallel with these climate outputs, and the resulting data directly informed design decisions for the parking structure. These analyses provided the basis for integrating passive lighting systems, ventilation orientations, plant species selection, building envelope strategies, and ecosystem components. The developed scenarios correspond closely with the climate-responsive design principles outlined below. Based on the information provided by this software, key design decisions were guided, including passive lighting strategies (glass ceilings, translucent covers, light wells), natural ventilation orientations (west and northeast openings, vertical air chimneys, semi-open buffer areas), plant species selection (shade-tolerant epiphytes, ferns, succulents, ivy species, and hydroponic plants), and integration of ecosystem components (modular plant units, misting systems, biofilters).

The "Illumination Range" graph for the study area reveals the distribution of light intensity recorded during daylight hours throughout the year. According to the graph, which compares direct normal and global horizontal light values monthly, both types of light reach high levels between May and August, while light values decrease significantly in December, January and February. Looking at the year in general, it is seen that diffuse light is more stable than direct light in Rize, where cloudiness is high, and this should be considered in design decisions. In this context, the glass ceiling applications proposed in the study provide maximum utilization of daylight in the interior space and are supported by shading elements to prevent overheating in summer. Likewise, it is proposed to support energy production with solar panels in the summer months with high light intake, and artificial lighting support is planned for low-light winter months. All these suggestions show the applicability of passive lighting strategies in climates where diffuse light is effective and reveal that the energy efficient scenarios developed in the context of the re-functionalization of underground parking lots coincide with climate data (Figure 3).

According to the wind wheel graph of Rize province, the dominant wind directions throughout the year are west (W), southwest (SW) and northeast (NE), and air movements from these directions are frequently repeated throughout the year. Although the average wind intensity is low, these regularly blowing prevailing directions offer significant potential for natural ventilation strategies. Especially considering the high relative humidity (70% and above) and moderate temperature ranges (20–24 °C), controlled airflow and humidity management are of great importance to ensure thermal comfort inside the building. Accordingly, the scenarios developed within the scope of our study, which include natural ventilation orientations, vertical air chimneys and semi-open buffer areas open to the wind (such as atrium, green wall, glass roof openings), are directly in line with climate data. In line with the wind direction data, positioning these openings on the west and northeast axes will increase cross-air flow and strengthen ventilation and moisture control in the underground building layers. At the same time, the positioning of vertical green surfaces in

these directions will not only provide ecological and visual contribution to the building but will also provide strategic benefits in terms of filtering the microclimatic effect (Figure 4).

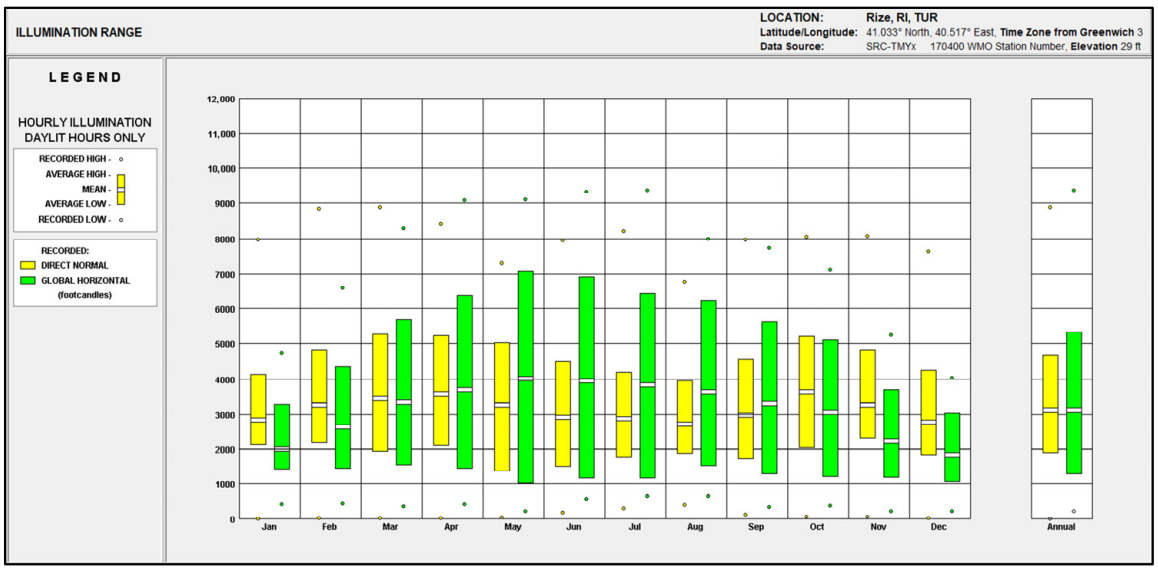


Figure 3. Illumination Range graph for Rize province.

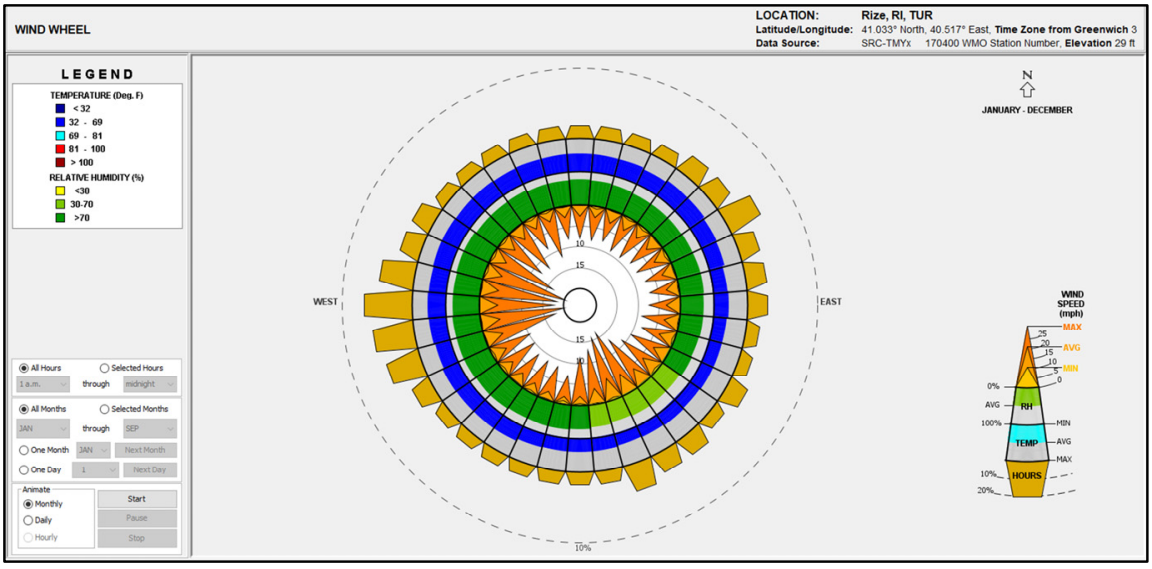


Figure 4. Wind Wheel Graph for Rize Province.

According to the monthly daily averages graph of the province, it shows the hourly change in temperature and radiation values throughout the year and the comfort range. The graph provides comprehensive reading in terms of natural lighting and passive heating strategies by presenting dry bulb, wet bulb and radiation (global, direct and diffuse) values together. Accordingly, temperatures hover in the 20–26 °C range for most of the year, which means that visual and physical continuity with outdoor spaces can be established. Radiation curves show that global and diffuse radiation is high, especially between March and September, while direct radiation remains low due to cloudiness. This suggests that the passive lighting strategies proposed in our design scenarios, such as glass ceilings, translucent covers and light surfaces, will be supportive for a significant part of the year. In addition, the high level of diffuse light reduces the need for photosynthetic LEDs and increases the year-round sustainability of natural light-powered vegetative systems. During

the winter months, when radiation is low, it is recommended to complement these systems with supplementary LED lighting. In line with these data, heat gain and natural lighting scenarios in underground building layers seem to be compatible with Rize's climate data in terms of both energy efficiency and indoor comfort (Figure 5).

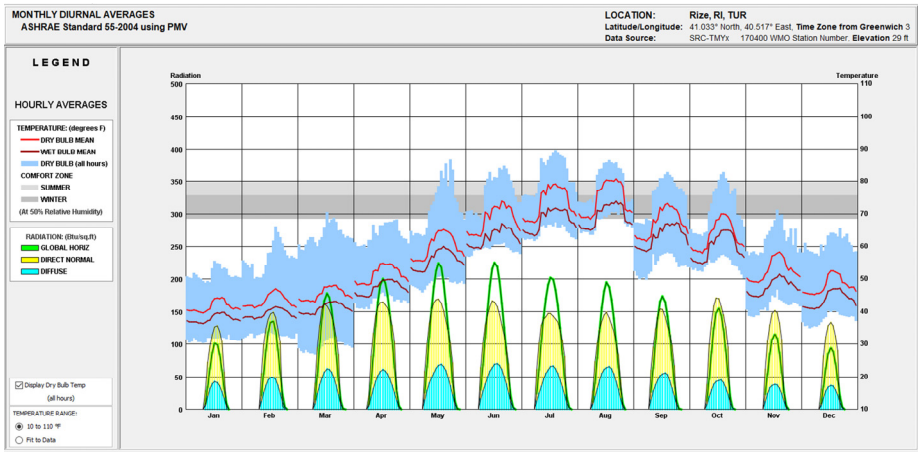


Figure 5. Monthly Daily Averages Graph for Rize Province.

The irradiance range graph for the site shows the hourly averages of global horizontal, direct normal and total surface irradiance values throughout the year. The graph reveals that total surface radiation (orange area) reaches particularly high values between April and September; direct radiation (green bar) is also effective during this period. This supports the applicability of passive and active light control solutions such as glass ceilings, transparent covers, solar panels and light well systems, which are prominent in the design scenarios. At the same time, the proposed sloping surface integration and the use of southeast-west axis openings based on directional radiation data will increase solar energy gain and increase both indoor natural lighting and photovoltaic panel efficiency. Surface irradiance of over 250 Btu/ft^2-hours for about seven months of the year provides an energy profile that solar panels can work effectively, making it possible to utilize the roof surfaces of underground parking lots or atrium spaces as energy generation surfaces. In December-February, when irradiance is low, it is recommended that these systems should be alternately designed to work on insulation instead of passive heating (Figure 6).

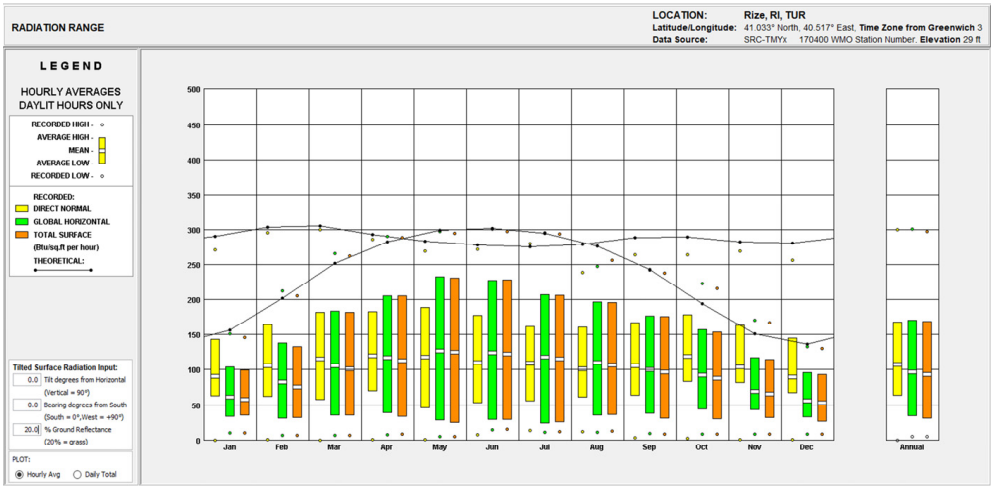


Figure 6. Annual irradiance range graph for Rize province.

The psychometric graph revealed that only 20.7% of the annual hours fall within the thermal comfort range under the selected passive design strategies. This result suggests that high humidity and low winter temperatures in similar locations such as Rize limit the effectiveness of purely passive systems [76,77]. Furthermore, the illumination analysis showed significant daylight utilization during winter months (November-February), justifying the integration of photosynthetic LED lighting to support low-light plant species such as *Spathiphyllum* and *Zamioculcas* [78] (Figure 7).

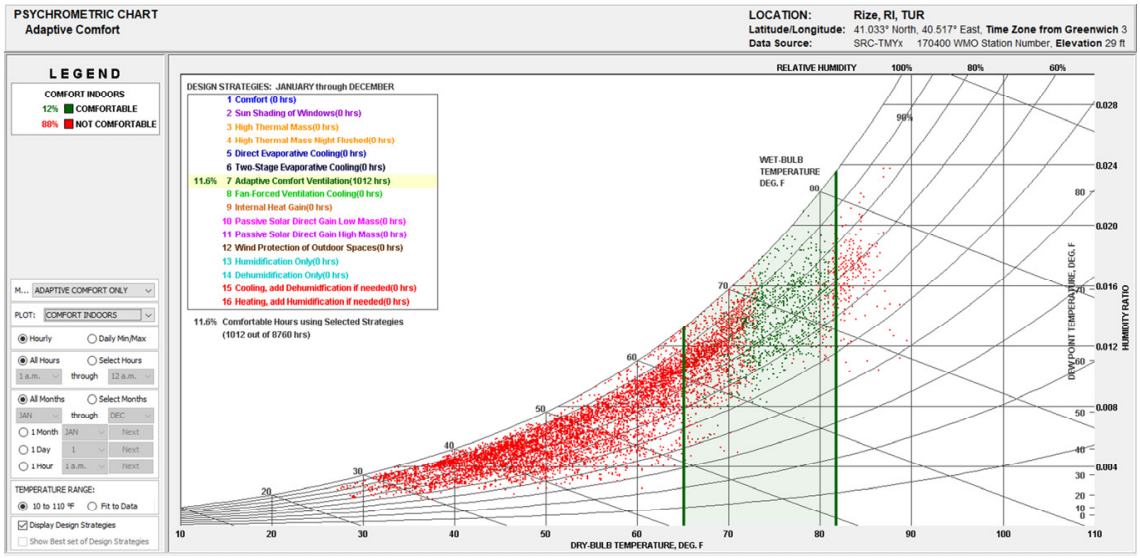


Figure 7. Psychrometric Graph for Rize Province.

The solar shading diagram for Rize province allows for the analysis of solar radiation, temperature ranges and shading needs at different periods throughout the year. According to the data in the diagram, temperatures above 24° C, defined as the hot period, are encountered for only 103 h a year, and only 28 h of this period are shaded. While the comfort temperature range of 20–24° C lasts 228 h per year, the shading requirement is again quite limited. In contrast, temperatures are below 20° C for most of the year; a total of 1466 h of sunlight is needed in this "cold" category, but only 275 h of this time is shaded. These findings suggest that designs in the Rize climate should focus mainly on directing sunlight indoors. Especially in the winter months, the sun moves at low angles, so glass openings and short eaves are recommended to increase passive heat gain on the south facades. In summer, the sun moves at high angles, making it possible to provide natural comfort with horizontal shading elements. Maximum utilization of daylight in areas with glass ceilings supports plant growth by increasing both passive heat gain and photosynthetically active radiation (PAR) levels in the interior. Similarly, it is emphasized in the literature that effective directing of sunlight provides significant effects on indoor temperature regulation, efficient resources and plant health [79,80]. In this context, the design strategies are designed as a multi-faceted sustainability approach that combines the use of natural light, passive air conditioning and plant system efficiency (Figure 8).

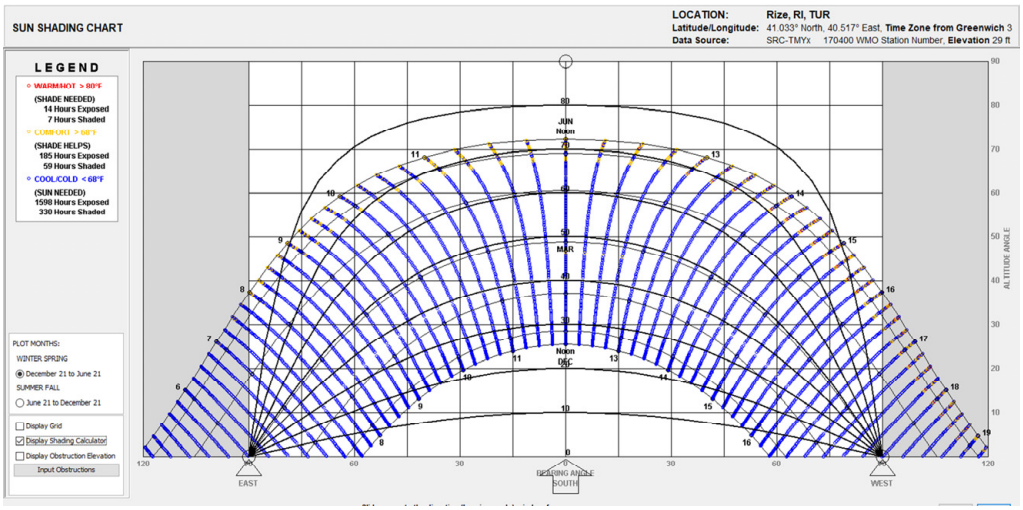


Figure 8. Sun Shading Diagram for Rize Province.

The adaptive comfort diagram for Rize province shows the relationship between dry bulb temperature and relative humidity during the 24 h periods of each month and the extent to which they overlap with the comfort zone. According to the graphic data, the relative humidity is quite high throughout the year; it reaches 85–95% levels especially in January, February, November and December, and hovers in the 70–85% band in the summer months. In contrast, temperatures are generally low and only approach the comfort range for a limited period between June and September. This reveals that high humidity and low temperature conditions are dominant in Rize. These climatic characteristics play a decisive role in both the selection of vegetation systems and indoor comfort [81,82]. Consistently high humidity provides a favorable environment for the growth of moss panels, epiphytic plants (e.g., *Tillandsia* spp.) and shade-tolerant species, supporting their moisture balancing function. On the other hand, low temperatures increase the importance of designs that aim to make the most of passive heat gain and daylighting. In this context, biophilic systems offer not only aesthetic but also functional solutions that support climatic adaptation and indoor air conditioning. The adaptive comfort diagram contributes to shaping these design decisions based on climatic data (Figure 9).

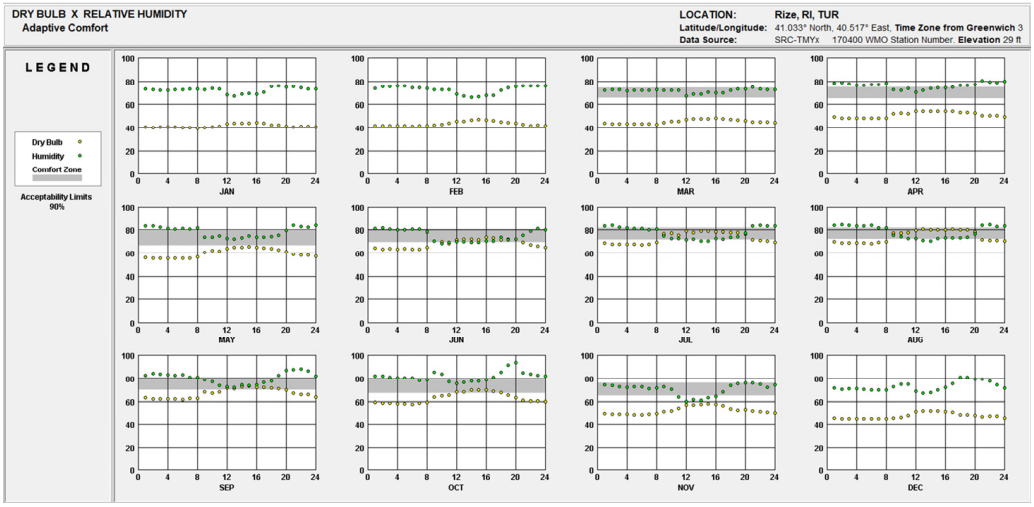


Figure 9. Adaptive Comfort Diagram Created for Rize Province.

According to the design guide, the city's climatic data shows that passive design strategies are feasible in underground structures. While solutions such as glass ceilings and light chimneys support natural lighting during periods when diffused light is dominant, wind data necessitates that openings should be focused on west and northeast directions. Temperature and humidity values require green surfaces and ventilation arrangements to be planned in accordance with microclimatic data. The data obtained from the findings of the climatic analysis served as a guide in the design process and played a decisive role in making spatial decisions. Considering the microclimatic conditions specific to Rize, such as high humidity, low insolation and heavy rainfall, a multi-layered approach was adopted, from plant species to be used indoors to building envelope strategies, from lighting systems to energy generation models. In this context, scenarios have been created in which both passive and active systems are used together to increase user comfort and ecological performance. The design proposals were supported by data on the existing structural boundaries and potential functional transformation of the site; accordingly, decisions based on basic principles such as energy saving, visual comfort, sustainable water management and biophilic interaction were developed.

5. Discussion

In this study, three different design scenarios were developed for the ecological re-functioning of underground parking lots. Each scenario was shaped in line with the existing physical characteristics of the area, user needs and local climate data of Rize province. The energy and heat loss calculations included in the study were made through predictive models based on the example scenarios. All values assume that the systems operate at average efficiency and may vary according to local climatic conditions, placement of system components, maintenance status and other environmental factors. The proposals cover different ecological objectives such as low-carbon energy strategy, microclimatic balance, acoustic comfort, food production. The scenarios detail design decisions such as plant species used, system components, light and water management, surface solutions, and the expected environmental impacts and operational needs of each. Accordingly, the design decisions presented are based on a scenario-based approach developed in the light of available climatic data. Artificial intelligence-supported visuals are design images that are proposals reflecting the spatial principles for the ecological functionalization of underground parking lots and represent conceptual analyses.

5.1. Artificial Intelligence Supported Scenarios

5.1.1. Scenario 1: Passive Green Wall Transformation

This scenario is based on a low-tech, easy-to-maintain green surface wall strategy that aims to create ecological value on the interior walls of underground parking lots without increasing energy consumption. The systems used are generally hydroponic, suitable for manual irrigation and shade-tolerant plants (Figure 10).

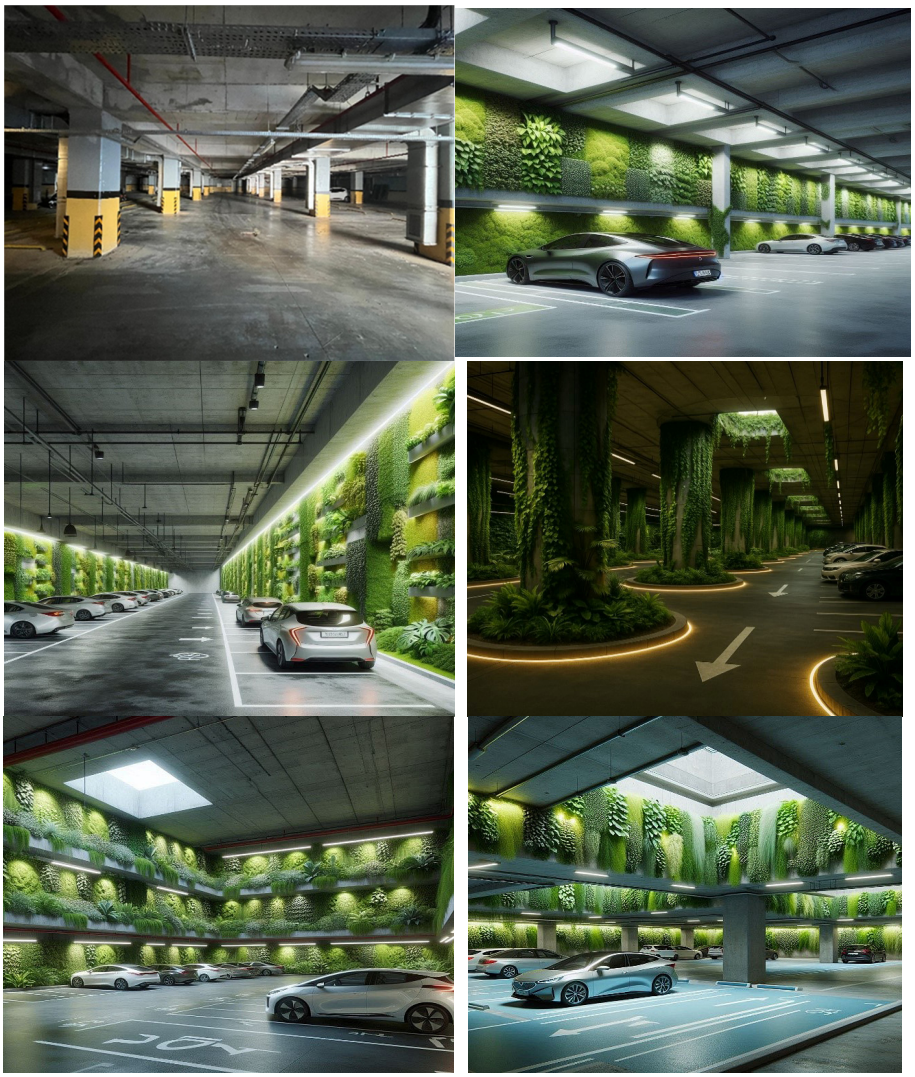


Figure 10. Passive Green Wall Transformation Alternative Designs.

Design Components and systems:

- Plants: Shade plants such as *Spathiphyllum*, *Aglaonema*, *Zamioculcas* were selected. These species can also survive in low light conditions.
- Surfaces: Modular moss panels and porous surface coverings contribute to both thermal insulation and acoustic improvement.
- Lighting: LED-assisted but low-consumption lighting provides visual comfort.
- Relationship with Climate Data: Rize's diffuse light characteristics and high humidity allow these systems to function sustainably without much outside intervention.

Expected Effects:

- 20% reduction in thermal transmittance of the wall system.
- Annual energy savings of approximately 1400 kWh.
- An annual reduction of approximately 560 kg in CO_2 emissions is foreseen.
- Positive effects on indoor air quality, visual comfort and user psychology.
- Thanks to the acoustic contribution of moss panels, acoustic comfort is provided by reducing echo and noise level.
- It has high applicability as a low-cost and low maintenance solution.

The observed improvements in comfort and sound quality mainly result from the moss panels' porous and moisture-retentive structure, which functions as both insulation

and sound absorber. This dual performance supports thermal stability and microclimatic balance in confined areas.

5.1.2. Scenario 2: Active Modular Plant Systems

This scenario includes active, automation-supported green surfaces integrated into wall systems. Supported by photosynthetic LEDs, the systems offer multifaceted contributions such as humidity control, thermal insulation, CO_2 reduction and enhancement of aesthetic quality (Figure 11).

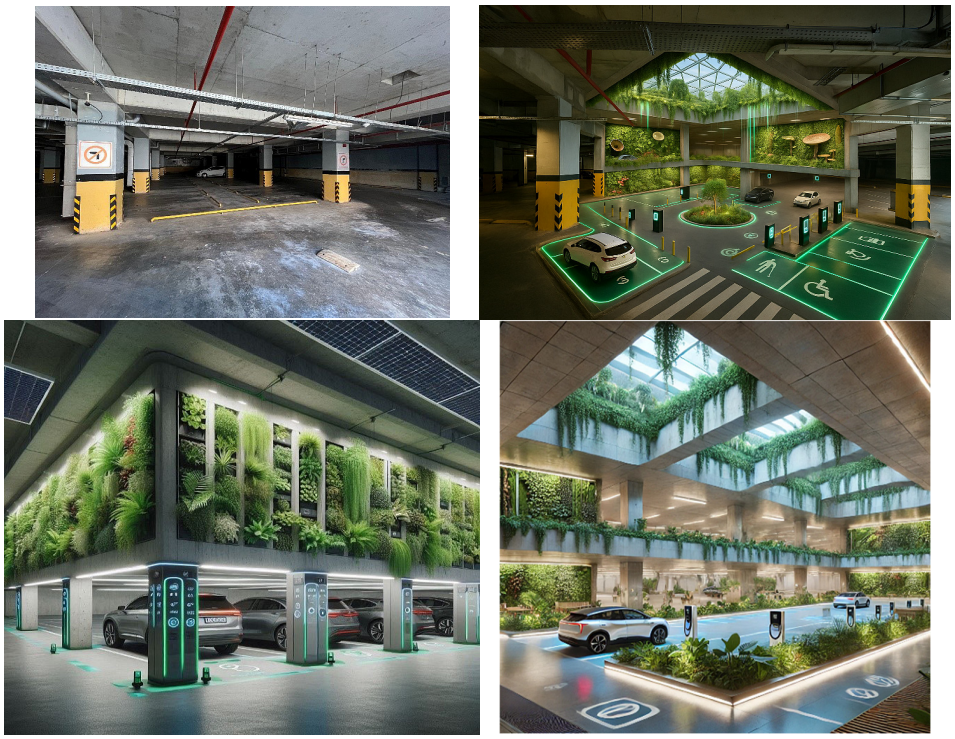


Figure 11. Active Modular Plant Systems Alternative Designs.

Design Components and Systems:

- Plants: Epiphytic species (e.g., *Tillandsia*) and ferns were selected and plants that can tolerate high humidity were preferred.
- System: Smart irrigation supported by a gray water cycle, LED lighting and photosynthetic wavelengths.
- Energy: The system is fed by solar panels, providing a net energy gain.
- Relationship with Climate Data: While Rize's high annual rainfall and humidity provide advantages in meeting the biological needs of plants, limited natural light conditions necessitate LED support.

Expected Impact:

- The heat transmission coefficient of the wall system is reduced by 35% and the U-value is reduced to 0.78 W/m^2K.
- An annual energy saving of approximately 2450 kWh is expected.
- 980 kg/year CO_2 emission reduction is achieved.
- It contributes to maintaining the humidity balance of the space.
- Improves user experience in terms of aesthetic and biophilic quality.
- It is feasible with moderate cost and moderate maintenance requirements.

The stronger humidity control in Scenario 2 is explained by the continuous evapotranspiration of epiphytic species and the feedback effect of automated irrigation and ventilation modules, which maintain microclimatic equilibrium.

5.1.3. Scenario 3: Intensive Planting + Experimental Micro-Farming

This scenario envisages the repurposing of the glass-roofed or naturally ventilated upper sections of the underground parking lots with dense green surfaces and limited-scale micro-farming practices. Food production is no longer the primary objective, but is instead treated as an educational, symbolic and biophilic contribution (Figure 12).

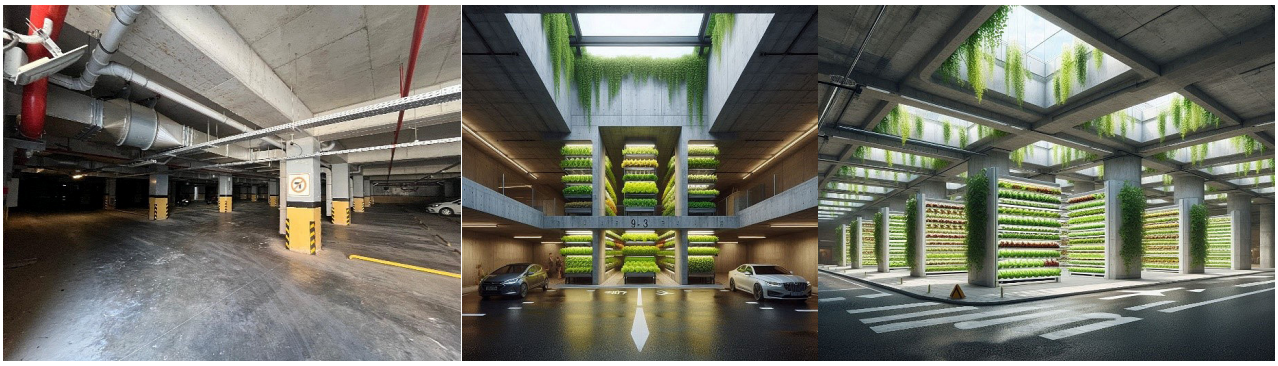


Figure 12. Experimental Micro-Farming Alternative Designs.

Design Components and Systems:

- Plants: Plants with low pollutant sensitivity, such as lettuce and basil, are used in the experimental production areas, while hanging plants such as *Hedera helix* and *Chlorophytum* form the backbone of the system.
- Lighting: Natural light is supported by photosynthetic spectrum LEDs and a glass ceiling.
- Energy: 10,400 W panels produce approximately 5000 kWh per year.
- Water System: Water efficiency is ensured with gray water usage and sensor irrigation system.
- Relationship with Climate Data: The variability of natural light in Rize makes it necessary to use a combination of both natural and artificial light in agricultural scenarios. At the same time, the high humidity level of the region increases the efficiency of hydroponic systems.

Expected Impact:

- With the integration of wall and ceiling systems, a 45% reduction in thermal transmittance is achieved and the U-value decreases to 0.66 W/m^2K.
- Annual energy savings of approximately 3150 kWh are achieved.
- An annual reduction of approximately 1260 kg in CO_2 emissions is foreseen.
- Sustainable food production is ensured within the city, creating opportunities for direct participation for users.
- Photosynthetic LEDs and daylight-assisted agricultural systems contribute to microclimatic regulation.
- This solution has the highest ecological impact, but also high cost and high maintenance needs.

Scenario 3 achieves the most stable temperature and humidity due to the combined influence of hydroponic water cycles and diffuse light distribution, providing both ecological functionality and user comfort.

Comparing these three scenarios, each has different advantages and disadvantages. While the Passive System offers a basic approach with low cost and low maintenance, it is more limited in terms of energy savings and environmental contributions. The Active Modular System, on the other hand, requires moderate cost and maintenance, while achieving higher energy savings and CO_2 reductions, as well as improved performance in terms of plant diversity and user experience. The Experimental Micro-Agriculture Scenario has the highest cost and maintenance requirements, but offers maximum energy savings, CO_2 reduction and plant species diversity, and has the most positive impact on user experience. Therefore, economic resources, maintenance capacity and environmental objectives should be considered when making the choice (Table 3).

Table 3. Energy Performance Comparison of Different Scenarios.

Criteria	Scenario 1: Passive System	Scenario 2: Active Modular	Scenario 3: Intensive Agriculture
U-Value (W/m^2K)	0.96	0.78	0.66
Energy Savings (kWh/year)	1.400	2.450	3.150
CO_2 Reduction (kg/year)	560	980	1.260
Plant Species Diversity	Middle	High	Highest
Cost	Low	Middle	High
Maintenance Requirement	Less	Middle	High
User Experience Impact	Middle	High	Highest

5.2. Total Energy Performance Assessment by Scenarios

In this phase of the study, to better assess the impact of green wall systems on building energy performance, the heat loss and gain of the buildings were analyzed with a simplified model. In the model, the heat loss was calculated using the heat transmission coefficients (U-values) of the walls corresponding to the different scenarios, considering the total range of effect of the three scenarios on the heat transmission coefficient. In this context, the total annual energy savings and CO_2 emission reduction values of three different green wall strategies starting from passive system to active modular system and dense planting scenario are examined in detail.

5.2.1. Heat Loss/Gain and Energy Efficiency Analysis

To evaluate the contribution of the green wall systems of the area to the building energy performance, the heat loss and gain of the buildings were analyzed with a simplified calculation model. In the model, the initial heat transmission coefficient (U-value) of a reinforced concrete wall was taken as 1.20 W/m^2K, and new scenario-specific U-values were calculated by considering the improvement rates achieved in this value under different green wall scenarios.

The total effect range of the three scenarios on the coefficient of thermal transmittance varies between 20 and 45% and the corresponding U-values were determined as 0.96, 0.78 and 0.66 W/m^2K, respectively. These ratios are based on experimental studies reported in the literature [80,82,83]. These studies have shown that green façade systems can improve U-values by 10% to 50%. The annual energy savings and carbon emission reductions for each scenario are calculated as follows:

- In the calculation of energy savings, the savings rate was determined based on the difference between the improved U-values and the base (reinforced concrete) U-value and the energy gain was calculated based on the total annual consumption (see 33).

- CO_2 reduction was calculated by multiplying the annual energy savings values obtained by the IEA (2021) emission coefficient for Turkey of 0.40 $kgCO_2/kWh$ (Table 4).

Table 4. Energy and Carbon Performance of Green Facade Scenarios.

Scenario	New U-Value (W/m^2K)	Energy Savings (kWh/year)	CO_2 Reduction (kg/year)
Passive Green Wall (20% improvement)	0.96	1.400	560
Active Modular System (35%)	0.78	2.450	980
Intensive Planting (45%)	0.66	3.150	1.260

These results show that green wall systems provide not only aesthetic or psychological contribution, but also tangible energy efficiency and carbon emission reduction (Figure 13). Similar rates of energy gain have been reported in some studies and the findings in this study are consistent with the literature [80,82].

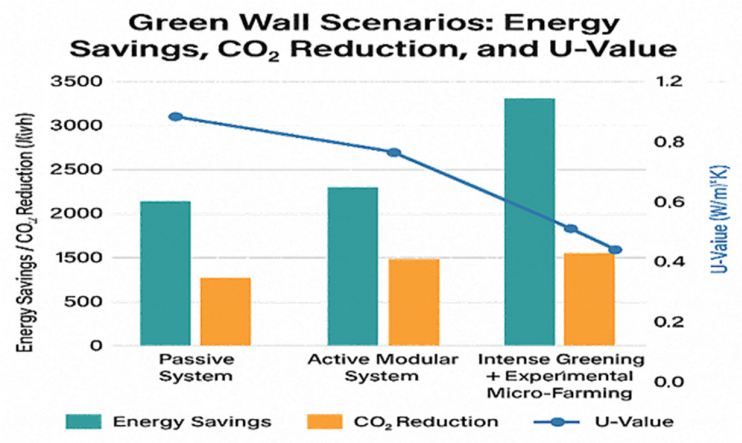


Figure 13. Scenario-based Performance Chart of Green Wall Strategies.

5.2.2. Plant Systems and Ecological Functions

Plant species used in underground spaces are particularly adaptable to low light conditions and require minimal maintenance. In this context, plants such as *Spathiphyllum*, *Zamioculcas*, *Aglaonema*, *Tillandsia* spp. and *Nephrolepis* spp. are important components that support the ecological functions of the interior space [84,85]. NASA's "Clean Air Study" conducted in 1989 and many subsequent studies have shown that these species have positive effects on improving indoor air quality, the absorption of volatile organic compounds (VOCs) and thus the psychological well-being of users [84,86]. These plants play a supportive role on both physical and psychological health by reducing toxic gases in indoor spaces [87]. In addition, moss panels used indoors increase acoustic comfort with functions such as sound insulation and moisture balance [88]. Research on the acoustic performance of green wall systems in particular shows that these applications improve indoor sound quality by shortening the reverberation time [89]. As a result, the application of these vegetative systems increases psycho-physiological satisfaction and contributes to indoor health in line with nature-integrated design principles. The positive effects of biophilic and nature-imitating space design on human psychology, physiology and general health are supported by numerous scientific studies [90,91]. Beyond restorative effects, the presence of nature in indoor environments has also been shown to influence behavioral orientations. For instance, empirical findings highlight that perceived restorativeness and nature connectedness serve as mediators linking indoor greenery with improved quality

of life and prosocial tendencies [8]. Similarly, meta-analytical research demonstrates that restorative experiences are consistently stronger in natural settings compared to built ones, reinforcing the idea that even limited biophilic interventions in enclosed spaces can shape users' affective states and interaction patterns [10]. These insights indicate that the transformation of underground structures into biophilic interiors may not only enhance individual well-being but also foster behavioral shifts aligned with sustainable urban living.

5.2.3. Energy, Lighting and Irrigation Systems

Optimized energy performance and sustainable water management are critical in modern vertical farming and green wall applications. In this context, the scenarios include LED-based photosynthetic lighting systems, sensor-controlled irrigation technologies and solar panel integration. LED panels were integrated on a total surface area of 100 m^2 to support plant growth. A 60 m low-voltage LED system is envisaged for directional lines. Artificial lighting has a high impact on energy consumption, accounting for more than 50% of energy consumption in vertical farming systems, especially in indoor areas. Ventilation and irrigation systems have significant shares in total energy consumption [79,92]. In a hypothetical scenario, the integration of solar energy systems can generate an average of 5000 kWh of electricity per year with approximately 10.400 W panels placed on glass roofed areas. This production amount is calculated assuming an average radiation duration of 3.5 h/day in regions with moderate insolation such as Rize. The payback period of the system is estimated to be approximately 11 years depending on the electricity tariff and investment cost [93]. This is a promising indicator for the effective use of renewable energy sources in vertical farming and urban green applications. In addition, gray water recycling and smart irrigation systems contribute to sustainable water use; although the energy costs of these technologies are affordable, their ecological benefits are frequently emphasized in the literature [94,95]. Smart irrigation prevents water waste and optimizes plant health by dosing according to the real-time water needs of the plant [96].

5.2.4. Heat Loss and Gain Analysis: Simplified Thermal Model

Heat loss and gain is one of the key parameters directly affecting the energy performance of buildings. The simplified heat transfer model used in this study is intended to calculate the estimated energy loss or gain through convection and conduction through building elements (e.g., walls).

$$Q = U \times A \times \Delta T \times t \quad (1)$$

Equation (1): Heat transfer calculation equation through the building envelope.

This formula calculates the heat flow depending on the wall area, material properties (U value), inside-outside temperature difference and time [97]. Application parameters:

- Wall Area (A): 822 m^2
- Mean Temperature Difference (ΔT): In Rize winter season, the indoor average was taken as 20 °C and the outdoor average was taken as 8 °C, and the difference was determined as 12 °C [98].
- Duration (t): 6 months * 30 days/month * 24 h/day = 4320 h
- Material and System Scenarios:
- Reinforced concrete wall U = 1.2 U = 1.2 U = 1.2 U = 1.2 W/m^2K (TS 825, 2018)
- Passive Green Wall (20% improvement): U = 0.96 U = 0.96 U = 0.96 U = 0.96 W/m^2K
- Active System (35% improvement): U = 0.78 U = 0.78 U = 0.78 U = 0.78 W/m^2K
- Dense Planting (45% improvement): U = 0.66 U = 0.66 U = 0.66 U = 0.66 W/m^2K

It shows the heat loss of different green wall application scenarios over a 6-month period. Passive green wall applications reduce heat loss by about 20% compared to conventional reinforced concrete walls, while active systems increase this rate to 35%. Dense planting, on the other hand, provides up to 45% heat loss improvement due to the thickness and density of the vegetative layer (Table 5). These results clearly demonstrate the contribution of green walls to building energy efficiency and show that they play an important role in sustainable building design [80,99].

Table 5. Estimated heat loss values for wall systems (kWh).

Scenario	U-Value (W/m^{2}K)	6 Monthly Heat Loss (kWh)
Passive Green Wall (20% improvement)	0.96	40.908 kWh
Active System (35% improvement)	0.78	33.237 kWh
Intensive Planting (45% improvement)	0.66	28.124 kWh

5.2.5. Distribution and Functions of Vegetation Systems by Area

Within the scope of the design, different plant groups were placed according to the light level and humidity regime of the areas; each species group was selected to be compatible with the microclimatic conditions of the location. This approach aims to increase spatial functionality and user comfort in accordance with biophilic design principles [90,91]. Accordingly, the function and distribution of the species used in the area is envisaged as follows:

- Shade-Tolerant Indoor Plants (*Spathiphyllum*, *Zamioculcas*, *Aglaonema*): These species were used in areas without glass ceilings and in full shade. They were preferred in modular green wall systems due to their ability to photosynthesize in low light conditions and the density of their leaf tissues [84,85].
- Epiphytic Species (*Tillandsia* spp.): These species, which do not require direct soil, were placed in well-lit niches and hanging systems under glass ceilings. In addition to their aesthetic contribution, they helped stabilize ambient humidity [100].
- Moss Panels: Acoustic comfort is provided thanks to their sound absorbing properties by using them on semi-open parking lot surfaces and interstitial spaces. It also contributed to indoor quality by creating aesthetic and natural surfaces in areas with constant humidity [101].
- Creeping Species (*Hedera helix*, *Pilea* spp.): It was evaluated as a ground cover at ground edges and micro-topographic elevations. They provided both microhabitat and ecological continuity by creating a naturalization effect on transition surfaces [102].
- Hydroponic Aromatic Plants (e.g., basil, lettuce): Grown in raised systems under glass ceilings in areas of high light intake and supplemented with photosynthetic LED lighting. These systems provided an experimental model for in situ micronutrient production on an urban scale [79,103].
- Bioluminescent Species/Fungi (e.g., *Armillaria* spp.): Placed in semi-dark niches, they were evaluated both as an experimental landscape element and as a source of atmospheric light. These species created an experiential layer that goes beyond traditional lighting [104].

5.2.6. Cost–Return Analysis Energy Systems

To ensure the long-term sustainability of the proposed systems, the economic feasibility was evaluated by calculating the payback period (P_b) which represents the number of years

required for the system to recover its initial investment through annual energy savings. The payback period was obtained using Equation (2):

$$\text{Recycling Period}(P_b) = \frac{\text{Total Cost installation}(C_T)}{\textit{Annual Energy Gain}(E_\alpha)} \quad (2)$$

Equation (2): Energy Return Analysis Equation

The "energy gain" here is obtained by multiplying the energy in kWh that the system generates or saves per year by the average unit price of electricity for Turkey for the year 2025, which is 3.00 ₺ /kWh (TEİAŞ, 2025 forecast data). In this context, as mentioned in the energy systems, for example, the proposed system consisting of 10.400 W solar panels is expected to generate approximately 5000 kWh of electricity per year. This production generates an economic return of 15,000 ₺ and gives a payback period of approximately 11 years when compared to the total installation cost of 160,000 ₺ (Table 6). Similar calculations were made for passive green walls, active modular system and algae panels and it was determined to what extent their energy performances are feasible in terms of cost-effectiveness. However, as emphasized in the literature [78,82], it is recommended to consider not only energy input but also indirect effects such as thermal insulation, moisture balance, acoustic comfort and psychological well-being in the evaluation of vegetative systems.

Table 6. Cost and energy-based payback periods of the proposed systems.

System	Total Installation Cost (₺)	Annual Energy Gain (₺)	Return Period (years)
Passive Green Wall	540.000 ₺	4.200 ₺	128 years
Active Modular System	600.000 ₺	7.350 ₺	81 years
Moss Panel	110.000 ₺	1.200 ₺	91 years
Solar Panel (Total)	160.000 ₺	15.000 ₺	11 years

5.3. Adaptation Assessment of Systems in the Context of Rize Climate

Rize is in the Eastern Black Sea Region of Turkey, with high humidity (75–85%), heavy annual rainfall (2300–2500 mm), limited sunshine duration (1200–1300 h per year) and distinctive climatic characteristics with an average annual temperature of 14 °C and 6–8 °C in winter [98]. These specific climatic conditions have a direct determining effect on the performance of the proposed crop and technological systems. In this context:

- Impact of High Humidity and Low Winter Temperatures: Green wall systems regulate ambient humidity and provide indoor moisture balance through transpiration and evaporation mechanisms through the leaves [83]. In addition, leaf and soil layers provide thermal insulation and minimize radiant heat loss, thus increasing energy efficiency in winter [105].
- Effect of Heavy Rainfall on Irrigation Needs: High annual rainfall is particularly advantageous for the sustainable development of epiphytic species (*Tillandsia* spp.) and moss panels. As these plants naturally thrive in environments with constant humidity, the rainfall regime in the region significantly reduces irrigation requirements [99,100].
- Impact of Limited Sunshine on Lighting: The average annual insulation of 1200–1300 h in the region provides sufficient natural light for plant growth, but especially areas with glass ceilings ensure that this light is used with maximum efficiency. In this way, plant physiology is supported by meeting the photosynthetically active radiation (PAR) requirement and the amount of artificial photosynthetic LED lighting needed can be reduced [79].

- Design and Ecological Integration: The selection of the system was made not only for aesthetic or functional purposes, but also to sensitively adapt to local climatic conditions. This brings multiple benefits such as energy savings, water management and user comfort as part of climate-based sustainability strategies [80].

6. Conclusions

In response to the growing demand for nature-based solutions in dense urban areas, this study proposes a scenario-based model for transforming underground parking lots into green interiors with ecological, energy-efficient, and biophilic qualities, aligned with climate-responsive design and sustainability principles. Passive, active, and experimental design strategies reveal the ecological and functional potential of these underutilized spaces. AI-supported simulations and climate-sensitive spatial planning tools demonstrate the contributions of green wall systems in enhancing energy efficiency, reducing carbon emissions, and improving user comfort. When combined with sustainable insulation technologies, passive green walls significantly boost energy performance and reduce emissions, supporting low-carbon targets in the building sector [106]. Green infrastructure also improves microclimate conditions, enables multi-layered water management, and mitigates urban heat island effects through renewable energy integration [107].

In microclimatic regions such as Rize—characterized by high humidity, limited sunlight, and mild temperatures—adaptive reuse of underground structures can yield ecological, spatial, psychological, and energy-related benefits. Although these conditions traditionally increase energy consumption, appropriate design interventions, including epiphytic plants, passive ventilation, and photosynthetic structures optimized for diffuse light, transform these challenges into advantages [78,81]. Moreover, Rize's steep topography and reliance on multi-story and subterranean construction make reconsidering underground spaces a spatial necessity. Sustainable transformation in such contexts therefore extends beyond new construction to the climate-based optimization of existing buildings, emphasizing adaptive reuse as a strategy for low-carbon urban development [82].

The model presented in the study offers a unique and necessary solution specific to the natural, structural and climatic context of Rize, both on a scientific and practical level. Comparative analyses of the three scenarios developed have led to recommendations that are scalable and have high implementation potential in terms of both energy performance and user experience. Green infrastructure systems [80,105], which are generally discussed in the literature in the context of exterior facades, roof gardens or open public spaces [80,105] were modeled for the first time in this study within the framework of the internal climate conditions of underground spaces, filling an important theoretical and practical gap in this respect.

Although underground structures are usually considered as invisible parts of urban infrastructure, this study reveals that these spaces can be transformed into multifunctional, user-friendly spaces with high environmental performance. The scenario-based approach comparatively evaluates different levels of technological and ecological solutions, from passive green walls to automated active systems and even micro-agriculture integration, and presents multidimensional outputs such as perceptual comfort, energy savings, carbon reduction and acoustic quality. The proposed design scenarios reflect different levels of technological integration and ecological contributions when compared with international examples. For example, Passive Green Walls are like the vertical green facades of the Oasia Hotel Downtown in Singapore, where these facades are covered with climbing plants to improve indoor environmental quality and reduce energy consumption [108,109]. Active Modular Plant Systems are parallel to the Pasona HQ underground farm in Tokyo, where hydroponic and soil-based production systems and controlled environmental conditions

optimize productivity and user well-being. Finally, the Experimental Micro Farming Units are compatible with advanced vertical and indoor agriculture initiatives, demonstrating that underground spaces can be used for sustainable food production. These comparisons reveal that each scenario both reflects current international trends and offers innovative strategies in urban interiors.

In addition, the planning of the selected plant species in coordination with local climatic data shows that the design is not only an aesthetic, but also a biophysical and psychological improvement strategy. The positive effects of indoor planting on occupant psychology and air quality have been frequently emphasized in the literature [84,86,90]; in this study, these effects are integrated with energy efficiency and microclimatic adaptation at the underground building scale.

The findings also enabled the evaluation of the proposed systems in terms of energy gain and cost-effectiveness relationship and produced realistic outputs at the scale of implementation. The ecological gains of high-cost solutions were found to be higher; in this context, a basis was prepared for decision-makers to develop planning models based on resource-cost-effectiveness balance. Economic payback analyses for energy systems are important in terms of making visible the long-term return of urban sustainability investments [93,95].

As a result, the transformation of parking lots into sustainable interiors is not only a structural re-function but also an effective strategy for the transformation of cities into livable spaces with low carbon emissions, climate resilience and integrated with nature. This study reveals that in sustainable urban transformation, underground spaces can be redesigned not only as technical infrastructure or temporary solution spaces, but also as multifunctional, climate-compatible and ecological living spaces. The proposed model offers a comprehensive transformation scenario in terms of user experience, indoor health and energy efficiency as well as the physical environment through the coordinated use of green infrastructure, human–nature connectedness approach, adaptive comfort theories and passive–active energy systems. In this respect, it makes a unique contribution to urban design and architecture literature by showing that sustainability-oriented interventions can be made not only in the upper levels but also in the lower levels of the urban space [80,90]. The flexible nature of the model provides a methodological framework that can be adapted to different climate zones, below-ground building typologies and user needs, making it replicable and developable not only regionally but also globally. In addition, by proposing a re-evaluation of the existing building stock in line with climate data, this study generates alternative low-carbon strategies for new construction and proposes an alternative planning model that focuses on deepening instead of horizontal expansion in the production of urban space. In this respect, it can be integrated into city-scale policies and planning to reduce carbon footprint [82,110].

Although the findings of this research are mainly conceptual, they also indicate several directions for practical implementation. The proposed transformation model can be incorporated into urban renewal strategies by integrating green retrofitting criteria into municipal design codes and zoning regulations. For local governments, such transformations may serve as low-cost tools for increasing urban green coverage and mitigating heat-island effects without consuming additional land. For private developers, underground greening offers opportunities to enhance property value and environmental certification potential. For residents, these interventions can improve everyday well-being by providing cooler, quieter, and more nature-connected urban experiences. Future pilot projects in existing underground parking structures could provide empirical data to refine this conceptual model and guide scalable implementation.

Future research can develop holistic approaches that evaluate not only physical but also social dimensions of space production processes by examining the behavioral, social and economic impacts of such scenarios in more depth in line with different urban scales, socio-economic user profiles, spatial inequality levels and intended uses. In this context, re-functionalization models based on contemporary urbanism theories such as participatory planning, spatial justice [111] and urban inclusiveness can be created by going beyond sustainability principles. At the same time, investigating issues such as qualitative user experiences, perceptual comfort levels and social acceptance of green infrastructure will create important new research areas for landscape architecture and urban planning disciplines.

Author Contributions: Conceptualization, B.A., S.B. and S.İ.; Methodology, B.A. and S.İ.; Validation, B.A., S.B. and S.İ.; Formal analysis, S.İ.; Investigation, B.A., S.B. and S.İ.; Resources, B.A. and S.B.; Data curation, B.A. and S.İ.; Writing—original draft, B.A. and S.İ.; Writing—review & editing, S.B. and S.İ.; Visualization, B.A.; Supervision, S.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: During the preparation of this manuscript/study, the authors used [Microsoft Designer, OpenAI DALL·E 3 and Artguru v2.0] for the purposes of [visualization]. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Labbé, M. Architecture of underground spaces: From isolated innovations to connected urbanism. *Tunn. Undergr. Space Technol.* **2016**, *55*, 153–175. [CrossRef]
2. UN-Habitat. *World Cities Report 2020: The Value of Sustainable Urbanization*; United Nations Human Settlements Programme: Nairobi, Kenya, 2020. Available online: https://unhabitat.org/sites/default/files/2020/10/wcr_2020_report.pdf (accessed on 17 October 2025).
3. Ashinze, U.K.; Edeigba, B.A.; Umoh, A.A.; Biu, P.W.; Daraojimba, A.I. Urban green infrastructure and its role in sustainable cities: A comprehensive review. *World J. Adv. Res. Rev.* **2024**, *21*, 928–936. [CrossRef]
4. Mohirta, A. Natural Lighting and Psychological Barriers in Underground Space. Ph.D. Thesis, Oxford Brookes University, Oxford, UK, 2012.
5. Fonseca, F.; Paschoalino, M.; Silva, L. Health and well-being benefits of outdoor and indoor vertical greening systems: A review. *Sustainability* **2023**, *15*, 4107. [CrossRef]
6. Berardi, U.; GhaffarianHoseini, A.; GhaffarianHoseini, A. State-of-the-art analysis of the environmental benefits of green roofs. *Appl. Energy* **2014**, *115*, 411–428. [CrossRef]
7. Kim, J.; Cha, S.H.; Koo, C.; Tang, S.K. The effects of indoor plants and artificial windows in an underground environment. *Build. Environ.* **2018**, *138*, 53–62. [CrossRef]
8. Baceviciene, M.; Jankauskiene, R. The mediating effect of nature restorativeness, stress level, and nature connectedness in the association between nature exposure and quality of life. *Int. J. Environ. Res. Public Health* **2022**, *19*, 2098. [CrossRef]
9. Berto, R. The role of nature in coping with psycho-physiological stress: A literature review on restorativeness. *Behav. Sci.* **2014**, *4*, 394–409. [CrossRef]
10. Menardo, E.; Brondino, M.; Hall, R.; Pasini, M. Restorativeness in natural and urban environments: A meta-analysis. *Psychol. Rep.* **2021**, *124*, 417–437. [CrossRef]
11. Bosone, L.; Bertoldo, R. The greater the contact, the closer the threat: The influence of contact with nature on the social perception of biodiversity loss and the effectiveness of conservation behaviours. *Sustainability* **2022**, *14*, 16490. [CrossRef]
12. McAllister, E.; Bhullar, N.; Schutte, N.S. Into the woods or a stroll in the park: How virtual contact with nature impacts positive and negative affect. *Int. J. Environ. Res. Public Health* **2017**, *14*, 786. [CrossRef]

13. Goel, R.K.; Singh, B.; Zhao, J. *Underground Infrastructures: Planning, Design, and Construction*; Butterworth-Heinemann: Oxford, UK, 2012. [CrossRef]
14. Neguritsa, D.L.; Alekseev, G.V.; Medvedev, E.A.; Tereshin, A.A. Assessment of the impact of the construction of underground structures with the use of special methods on underground pedestrian passengers. In Proceedings of the Conference on Physical and Mathematical Modeling of Earth and Environment Processes, Cham, Switzerland, 3–6 October 2022; Springer Nature: Cham, Switzerland, 2022; pp. 641–646. [CrossRef]
15. Nguyen, V.T. Integrating the 14 patterns of biophilic design into the convenience and comfort of apartments in Ho Chi Minh City. *E3S Web Conf.* **2023**, *403*, 03009. [CrossRef]
16. Gong, Y.; Szalay, Z.E.; Gulyás, J. Healthy dwelling: The perspective of biophilic design in the design of the living space. *Buildings* **2023**, *13*, 2020. [CrossRef]
17. Besner, J. Cities think underground—Underground space (also) for people. *Procedia Eng.* **2017**, *209*, 49–55. [CrossRef]
18. Delmastro, C.; Lavagno, E.; Schranz, L. Underground urbanism: Master plans and sectorial plans. *Tunn. Undergr. Space Technol.* **2016**, *55*, 103–111. [CrossRef]
19. Gelişen, G.; Bircan, D.K. Kentsel dönüşüm ile sürdürülebilir kent önerileri ve Selamsız örneği. *Kent Akademisi* **2019**, *12*, 501–518. [CrossRef]
20. Parriaux, A.; Blunier, P.; Maire, P.; Tacher, L. The DEEP CITY project: A global concept for a sustainable urban underground management. In Proceedings of the 11th ACUUS International Conference—Underground Space: Expanding the Frontiers, Athens, Greece, 10–13 September 2007; pp. 10–13.
21. Steemers, K. Energy and the city: Density, buildings and transport. *Energy Build.* **2003**, *35*, 3–14. [CrossRef]
22. Ulrich, R.S. View through a window may influence recovery from surgery. *Science* **1984**, *224*, 420–421. [CrossRef] [PubMed]
23. Xing, Y.; Gan, W.; Chen, Q.; Yu, P.S. AI-generated content in landscape architecture: A survey. *arXiv* **2025**, arXiv:2503.16435. [CrossRef]
24. Gallega, R.W.; Sumi, Y. Exploring the use of generative AI for material texturing in 3D interior design spaces. *Front. Comput. Sci.* **2024**, *6*, 1493937. [CrossRef]
25. Adewale, B.A.; Ene, V.O.; Ogunbayo, B.F.; Aigbavboa, C.O. A systematic review of the applications of AI in a sustainable building's lifecycle. *Buildings* **2024**, *14*, 2137. [CrossRef]
26. Shen, L.; Peng, Y.; Zhang, X.; Wu, Y. An alternative model for evaluating sustainable urbanization. *Cities* **2012**, *29*, 32–39. [CrossRef]
27. Zhuang, D.Y.; Ma, K.; Tang, C.A.; Liang, Z.Z.; Wang, K.K.; Wang, Z.W. Mechanical parameter inversion in tunnel engineering using support vector regression optimized by multi-strategy artificial fish swarm algorithm. *Tunn. Undergr. Space Technol.* **2019**, *83*, 425–436. [CrossRef]
28. Szopińska-Mularz, M.; Prokop, A.; Wikiera, M.; Bukowy, W.; Forsman, F.; Vikström, S. Adaptive reuse of urban structures as a driver of sustainable development goals: A systematic literature review. *Sustainability* **2025**, *17*, 4963. [CrossRef]
29. Fan, M.; Gu, Z.; Li, W.; Zhou, D.; Yu, C.W. Integration of a large green corridor with an underground complex—A low carbon building solution for urban climate revival. *Indoor Built Environ.* **2022**, *31*, 872–877. [CrossRef]
30. Ertas, M.; Bayındır, Ö. Sürdürülebilir kentsel dönüşüm. *Türkiye Arazi Yönetimi Derg.* **2020**, *2*, 1–9. Available online: https://dergipark.org.tr/tr/download/article-file/996732 (accessed on 17 October 2025).
31. Totaforti, S. Emerging biophilic urbanism: The value of the human–nature relationship in the urban space. *Sustainability* **2020**, *12*, 5487. [CrossRef]
32. Lee, E.J.; Park, S. Biophilic experience-based residential hybrid framework. *Int. J. Environ. Res. Public Health* **2022**, *19*, 8512. [CrossRef]
33. Martínez-Soto, J.; Suárez, L.A.d.l.F.; Ruíz-Correa, S. Exploring the links between biophilic and restorative qualities of exterior and interior spaces in León, Guanajuato, Mexico. *Front. Psychol.* **2021**, *12*, 717116. [CrossRef]
34. Can, S.A.; Kurtoğlu, D. Sürdürülebilir mimari kapsamında geliştirilen teknoloji ve ürünler. *Yalvaç Akad. Derg.* **2017**, *2*, 22–31. Available online: https://dergipark.org.tr/tr/download/article-file/395086 (accessed on 17 October 2025).
35. Daniels, P.; Baghdadi, O.E.; Desha, C.; Matthews, T. Evaluating net community benefits of integrating nature within cities. *Sustain. Earth* **2020**, *3*, 12. [CrossRef]
36. Han, B. Sürdürülebilir mimari ve enerji verimliliği konusunda yapılmış çalışmalar ve öneriler. *Hars Akad. Uluslararası Hakemli Kültür Sanat Mimar. Derg.* **2023**, *6*, 57–72. Available online: https://dergipark.org.tr/tr/download/article-file/3041010 (accessed on 17 October 2025).
37. Karayılanoğlu, G. Sürdürülebilir Kentleşme Ekseninde Kamusal Mekânın Kentsel İç Mekâna Dönüşümü: Helsinki Örneği. *İdealkent* **2020**, *11*, 1909–1932. [CrossRef]
38. Aftab, K.; Kulkarni, P.; Shergold, I.; Jones, M.; Dogramadzi, M.; Carnelli, P.; Sooriyabandara, M. Reducing parking space search time and environmental impacts: A technology driven smart parking case study. *IEEE Technol. Soc. Mag.* **2020**, *39*, 62–75. [CrossRef]

39. Ben Ahmed, M. Modern trends in green interior architecture applications with smart systems. *Int. J. Multidiscip. Stud. Art Technol.* **2024**, *7*, 1–21. [CrossRef]
40. Lehmann, S. Sustainable building design and systems integration: Combining energy efficiency with material efficiency. In *Designing for Zero Waste*; Routledge: London, UK, 2013; pp. 209–246. [CrossRef]
41. Rasheed, H. Modern trends in green interior architecture applications with smart systems. *Int. J. Adv. Eng. Civ. Res.* **2023**, *3*, 1–14. [CrossRef]
42. Amos Rex by JKMM Architects. Available online: https://l24.im/9ihgfCw (accessed on 12 September 2025).
43. The Guardian. Available online: https://l24.im/47bQIy (accessed on 12 September 2025).
44. Xu, H.; Zhao, G. Assessing the value of urban green infrastructure ecosystem services for high-density urban management and development: Case from the capital core area of Beijing, China. *Sustainability* **2021**, *13*, 12115. [CrossRef]
45. Beatley, T. *Biophilic Cities: Integrating Nature into Urban Design and Planning*; Island Press: Washington, DC, USA, 2011.
46. Tabassum, R.R.; Park, J. Development of a building evaluation framework for biophilic design in architecture. *Buildings* **2024**, *14*, 3254. [CrossRef]
47. Papina, C.; Crăciun, C. Nature—A Structural Component for Future Human Settlements? Biophilic City Approaches. In *Architecture Inspired by Nature: Experimenting Bionics*; Springer Nature: Cham, Switzerland, 2023; pp. 161–169. [CrossRef]
48. Ferreira, V.; Barreira, A.P.; Loures, L.; Antunes, M.D.C.; Panagopoulos, T. Stakeholders' engagement on nature-based solutions: A systematic literature review. *Sustainability* **2020**, *12*, 640. [CrossRef]
49. Peters, T.; D'Penna, K. Biophilic design for restorative university learning environments: A critical literature review and design recommendations. *Sustainability* **2020**, *12*, 7064. [CrossRef]
50. Yılmaz, Ş.E.; Ayten, A.M. A research on biophilic design patterns: The case of AGU as a biophilic campus. *Iconarp Int. J. Archit. Plan.* **2023**, *11*, 692–715. [CrossRef]
51. Khan, K. Understanding environmental quality of Samylai Eldership in Kaunas District using biophilic design principles. *Hum. Nat. Saf.* **2021**, 120–123. Available online: https://portalcris.vdu.lt/server/api/core/bitstreams/ffc58cce-145a-4df9-8e84-466caf8d5007/content (accessed on 12 September 2025).
52. Barth, M.; Boriboonsomsin, K. Real-world carbon dioxide impacts of traffic congestion. *Transp. Res. Rec.* **2008**, *2058*, 163–171. [CrossRef]
53. Shaffer, B.; Flores, R.; Samuelsen, S.; Anderson, M.; Mizzi, R.; Kuitunen, E. Urban energy systems and the transition to zero carbon—Research and case studies from the USA and Europe. *Energy Procedia* **2018**, *149*, 25–38. [CrossRef]
54. Berardi, U. A cross-country comparison of the building energy consumptions and their trends. *Resour. Conserv. Recycl.* **2017**, *123*, 230–241. [CrossRef]
55. Quaranta, E.; Dorati, C.; Pistocchi, A. Water, energy and climate benefits of urban greening throughout Europe under different climatic scenarios. *Sci. Rep.* **2021**, *11*, 12163. [CrossRef]
56. Kabisch, N.; Frantzeskaki, N.; Pauleit, S.; Naumann, S.; Davis, M.; Artmann, M.; Bonn, A. Nature-based solutions to climate change mitigation and adaptation in urban areas: Perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecol. Soc.* **2016**, *21*, 39. [CrossRef]
57. Zhao, Y.; Zhan, Q.; Xu, T. Biophilic design as an important bridge for sustainable interaction between humans and the environment: Based on practice in Chinese healthcare space. *Comput. Math. Methods Med.* **2022**, *2022*, 8184534. [CrossRef]
58. Hung, S.; Chou, W.; Chang, C. A study on practicing qigong and health benefits in biophilic urban green spaces. *Sustainability* **2021**, *13*, 1692. [CrossRef]
59. Asadzadeh, E.; Ahmadchali, M.Y. Analyzing design principles of biophilic neighborhoods. *Civil Eng. J.* **2018**, *4*, 2425–2436. [CrossRef]
60. Bahador, A.; Mahmoudi, M. Biophilic design: An effective approach during and post-pandemic. *Facilities* **2024**, *42*, 68–82. [CrossRef]
61. Peters, T.; Halleran, A. How our homes impact our health: Using a COVID-19 informed approach to examine urban apartment housing. *Archnet-Ijar Int. J. Archit. Res.* **2020**, *15*, 10–27. [CrossRef]
62. Im, J. Green Streets to Serve Urban Sustainability: Benefits and Typology. *Sustainability* **2019**, *11*, 6483. [CrossRef]
63. Onishi, A.; Cao, X.; Ito, T.; Shi, F.; Imura, H. Evaluating the potential for urban heat-island mitigation by greening parking lots. *Urban For. Urban Green.* **2010**, *9*, 323–332. [CrossRef]
64. Ye, W.; Gao, J.; Zhang, X.; Yu, C.W. Studies of relationship between ventilation, pollution exposure and environmental health of buildings. *Indoor Built Environ.* **2017**, *26*, 147–151. [CrossRef]
65. Cao, S.J.; Leng, J.; Qi, D.; Kumar, P.; Chen, T. Sustainable underground spaces: Design, environmental control and energy conservation. *Energy Build.* **2022**, *257*, 111779. [CrossRef]
66. Kondo, Y.; Tadokoro, Y.; Yoshino, H.; Imai, T. Study on Ventilation Efficiency in Underground Car Park: Part 1 Field Measurement of Age of Air. 2000. Available online: https://www.aivc.org/sites/default/files/airbase_13775.pdf (accessed on 17 October 2025).

67. Novalia, I.; Prakoso, W.A.; Tambunan, R.P.; Hasibuan, H.S. Green roofs in urban underground buildings: Design impact on perceptual comfort. *Int. J. Des. Nat. Ecodyn.* **2024**, *19*, 1479–1489. [CrossRef]
68. Çavdar, A.A. The effects of green wall applications on heating load and carbon emissions: Karadeniz Technical University. *Livenarch+ J.* **2025**, *2*, 137–153. Available online: https://dergipark.org.tr/tr/download/article-file/4663647 (accessed on 17 October 2025).
69. Vaverková, M.D.; Kosakıewıcz, M.; Krysińska, K.; Strzeszewska, K. Sustainable construction in post-industrial Ursus district in Warsaw: Biologically active areas on roofs and underground garages. *Inż. Bezp. Obiektów Antropog.* **2024**, *3*, 10–35. [CrossRef]
70. Lee, S.; Kim, Y. A Framework of Biophilic Urbanism for Improving Climate Change Adaptability in Urban Environments. *Urban For. Urban Green.* **2021**, *61*, 127104. [CrossRef]
71. Bullen, P.A.; Love, P.E. Adaptive reuse of heritage buildings. *Struct. Surv.* **2011**, *29*, 411–421. [CrossRef]
72. Thomson, G.; Newman, P. Urban fabrics and urban metabolism—From sustainable to regenerative cities. *Resour. Conserv. Recycl.* **2018**, *132*, 218–229. [CrossRef]
73. Tarek, S.; Ouf, A.S.E.D. Biophilic smart cities: The role of nature and technology in enhancing urban resilience. *J. Eng. Appl. Sci.* **2021**, *68*, 40. [CrossRef]
74. Milne, M.; Liggett, R.; Benson, A.; Bhattacharya, Y. Climate Consultant 4.0 develops design guidelines for each unique climate. In Proceedings of the American Solar Energy Society Meeting, Buffalo, NY, USA, 11–16 May 2009.
75. Attia, S.; Gratia, E.; De Herde, A.; Hensen, J.L. Simulation-based decision support tool for early stages of zero-energy building design. *Energy Build.* **2012**, *49*, 2–15. [CrossRef]
76. Givoni, B. *Climate Considerations in Building and Urban Design*; Wiley: Chichester, UK, 1998.
77. Milne, G.; LaRoche, P.; Morton, S. Why design matters: Comparing three passive cooling strategies in sixteen climate zones. In Proceedings of the ASES, Baltimore, MD, USA, 16–20 April 2013. Available online: https://energy-design-tools.sbse.org/papers/ASES05-Milne.pdf (accessed on 17 October 2025).
78. Manso, M.; Castro-Gomes, J. Green wall systems: A review of their characteristics. *Renew. Sustain. Energy Rev.* **2015**, *41*, 863–871. [CrossRef]
79. Kozai, T.; Niu, G.; Takagaki, M. *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*; Academic Press: London, UK, 2016.
80. Perini, K.; Rosasco, P. Cost–benefit analysis for green façades and living wall systems. *Build. Environ.* **2013**, *70*, 110–121. [CrossRef]
81. Maier, D. Perspective of using green walls to achieve better energy efficiency levels. A bibliometric review of the literature. *Energy Build.* **2022**, *264*, 112070. [CrossRef]
82. Pérez, G.; Coma, J.; Martorell, I.; Cabeza, L.F. Vertical greenery systems (VGS) for energy saving in buildings: A review. *Renew. Sustain. Energy Rev.* **2014**, *39*, 139–165. [CrossRef]
83. Ottelé, M.; Perini, K.; Fraaij, A.L.A. Comparative life cycle analysis for green façades and living wall systems. *Energy Build.* **2011**, *43*, 3419–3429. [CrossRef]
84. Wolverton, B.C.; Johnson, A.; Bounds, K. *Interior Landscape Plants for Indoor Air Pollution Abatement (NASA/TP-1989-102201)*; National Aeronautics and Space Administration: Washington, DC, USA, 1989. Available online: https://ntrs.nasa.gov/api/citations/19930073077/downloads/19930073077.pdf (accessed on 17 October 2025).
85. Gupta, K.; Puntambekar, K.; Roy, A.; Pandey, K.; Mahavir; Kumar, P. Smart environment through smart tools and technologies for urban green spaces: Case study: Chandigarh, India. In *Smart Environment for Smart Cities*; Springer: Singapore, 2019; pp. 149–194. Available online: https://link.springer.com/chapter/10.1007/978-981-13-6822-6_5 (accessed on 17 October 2025).
86. Li, D.; Wang, H.; Gao, Q.; Lu, M. Study on the ability of indoor plants to absorb and purify benzene pollution. *Sci. Rep.* **2024**, *14*, 13169. [CrossRef]
87. Lohr, V.I.; Pearson-Mims, C.H.; Goodwin, G.K. Interior plants may improve worker productivity and reduce stress in a windowless environment. *J. Environ. Hortic.* **1996**, *14*, 97–100. [CrossRef]
88. Azkorra, Z.; Pérez, G.; Coma, J.; Cabeza, L.F.; Burés, S.; Álvaro, J.E.; Urrestarazu, M. Evaluation of green walls as a passive acoustic insulation system for buildings. *Appl. Acoust.* **2015**, *89*, 46–56. [CrossRef]
89. Perini, K.; Ottelé, M.; Fraaij, A.L.A.; Haas, E.M.; Raiteri, R. Vertical greening systems and the effect on air flow and temperature on the building envelope. *Build. Environ.* **2011**, *46*, 2287–2294. [CrossRef]
90. Kellert, S.R.; Heerwagen, J.H.; Mador, M.L. *Biophilic Design: The Theory, Science, and Practice of Bringing Buildings to Life*; Wiley: Hoboken, NJ, USA, 2008.
91. Browning, W.D.; Ryan, C.O.; Clancy, J.O. *14 Patterns of Biophilic Design*; Terrapin Bright Green LLC: New York, NY, USA, 2014. Available online: https://www.terrapinbrightgreen.com/reports/14-patterns/ (accessed on 22 July 2025).
92. Jamali, M.; Soufizadeh, S.; Yeganeh, B.; Emam, Y. A comparative study of irrigation techniques for energy flow and greenhouse gas (GHG) emissions in wheat agroecosystems under contrasting environments in south of Iran. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110704. [CrossRef]

93. Saidur, R.; Rahim, N.A.; Islam, M.R.; Solangi, K.H. Environmental impact of wind energy. *Renew. Sustain. Energy Rev.* **2011**, *15*, 2423–2430. [CrossRef]
94. Li, F.; Wichmann, K.; Otterpohl, R. Review of the technological approaches for grey water treatment and reuses. *Sci. Total Environ.* **2009**, *407*, 3439–3449. [CrossRef] [PubMed]
95. Bos, J.J.; Brown, R.R. Governance experimentation and factors of success in socio-technical transitions in the urban water sector. *Technol. Forecast. Soc. Change* **2012**, *79*, 1340–1353. [CrossRef]
96. Pereira, L.S.; Paredes, P.; Jovanovic, N. Soil water balance models for determining crop water and irrigation requirements and irrigation scheduling focusing on the FAO56 method and the dual Kc approach. *Agric. Water Manag.* **2020**, *241*, 106357. [CrossRef]
97. ASHRAE. *ASHRAE Handbook—Fundamentals, SI ed.*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2017. Available online: https://studylib.net/doc/26335900/2017-ashrae-handbook-fundamentals-si (accessed on 17 October 2025).
98. Türkiye Cumhuriyeti Meteoroloji Genel Müdürlüğü (MGM). Available online: https://mgm.gov.tr (accessed on 22 July 2025).
99. Getter, K.L.; Rowe, D.B. The role of extensive green roofs in sustainable development. *HortScience* **2006**, *41*, 1276–1285. [CrossRef]
100. Cornejo, J.J.; Muñoz, F.G.; Ma, C.Y.; Stewart, A.J. Studies on the decontamination of air by plants. *Ecotoxicology* **1999**, *8*, 311–320. Available online: https://link.springer.com/article/10.1023/A:1008937417598 (accessed on 17 October 2025). [CrossRef]
101. Babakhani Fard, S.; Abravesh, M.; Gholipour Gashniani, M.; Mahmoudi Otaghvari, A. Design of acoustic panels in the walls in interior spaces of building by imitating the mechanism of ferns. *J. Fine Arts: Archit. Urban Plan.* **2021**, *26*, 59–70. [CrossRef]
102. Trepanier, M.; Boivin, M.A.; Lamy, M.P.; Dansereau, B. Green roofs and living walls. *Chron. Hortic.* **2009**, *49*, 5–7. Available online: https://www.actahort.org/chronica/pdf/ch4902.pdf#page=5 (accessed on 17 October 2025).
103. Despommier, D. *The Vertical Farm: Feeding the World in the 21st Century*; Thomas Dunne Books: New York, NY, USA, 2010.
104. Tavares, P.; Ingi, D.; Araújo, L.; Pinho, P.; Bhusal, P. Reviewing the role of outdoor lighting in achieving sustainable development goals. *Sustainability* **2021**, *13*, 12657. [CrossRef]
105. Cüce, A.P.M. Sustainable Insulation Technologies for Low-Carbon Buildings: From Past to Present. *Sustainability* **2022**, *14*, 12950. [CrossRef]
106. Cuce, P.M.; Cuce, E.; Santamouris, M. Towards sustainable and climate-resilient cities: Mitigating urban heat islands through green infrastructure. *Sustainability* **2025**, *17*, 1303. [CrossRef]
107. Alexandri, E.; Jones, P. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Build. Environ.* **2008**, *43*, 480–493. [CrossRef]
108. Wong, M.S.; Hassell, R.; Phua, H.W. Oasia Hotel Downtown, Singapore: A tall prototype for the tropics. *CTBUH Res. Pap. (III)* **2018**, *2018*, 12–19.
109. Al-Kodmany, K. Greenery-covered tall buildings: A review. *Buildings* **2023**, *13*, 2362. [CrossRef]
110. Sassi, P. *Strategies for Sustainable Architecture*; Taylor & Francis: London, UK, 2006. [CrossRef]
111. Soja, E.W. *Seeking Spatial Justice*; University of Minnesota Press: Minneapolis, MN, USA, 2010. Available online: https://books.google.com.tr/books?hl=tr&lr=&id=NkfEeomy-IUC&oi=fnd&pg=PR5&ots=h-3_mlZld7&sig=HnubByfM-goFWIm1PnlVBvdNVEM&redir_esc=y#v=onepage&q&f=false (accessed on 17 October 2025).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.