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THE DEVELOPMENT OF GREEN INFRASTRUCTURE IN MODERN BUILDINGS

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ABSTRACT

Since the 20th century, sustainable development has evolved in architectural design, and green infrastructures of plant-covered buildings have become popular. With the support of technology, various types of green infrastructures such as green roofs, green facades, and vertical gardens have become an integral part of urban architecture as a new architectural element. The green appearance of buildings can not only regulate the temperature and air quality, and control the amount of light inside the building, but also be a new architectural aesthetic element. However, the development of green infrastructure technology has not yet achieved the expected results in construction practice, and many existing vegetation buildings do not show qualified ecological and economic effects. As an emerging architectural approach, the natural elements of vegetation conflict with the elements of modern cities, and designers need to pay more attention to solving this problem and improve the user's participation and sense of identity in the architectural space.

Keywords:
Cities, Modern Buildings, Green Infrastructure, Green Roofs, Green Walls

GREEN INFRASTRUCTURE: HISTORICAL BACKGROUND, CONCEPT, AND ROLE IN MODERN CITIES

Historical Development of Green Infrastructure

The history of green infrastructure is extensive, dating back to ancient civilizations' exploration of integrating urban environments with nature. In ancient Babylon, the Hanging Gardens demonstrated how early humans could blend natural beauty into urban structures. Over time, this concept continued in the urban landscape designs during the Renaissance in Europe, such as the rooftop gardens in Italy. As the industrial era began and urbanization brought environmental challenges, the value of green spaces was reevaluated. In the 20th century, with the rise of the environmental movement, green infrastructure was recognized as a key component of urban sustainability (Loder, 2014). Today, with the acceleration of global urbanization, green infrastructure plays an essential role in mitigating urban heat island effects, improving air quality, and providing habitats for biodiversity (Loder, 2014).

Contemporary Development and Application of Green Infrastructure

The development of contemporary green infrastructure reflects a comprehensive consideration of environmental, social, and economic sustainability (Ali & Kheir, 2012). In modern cities, green roofs and walls serve not only as ecological engineering practices but also integrate with architectural aesthetics and urban design. For instance, Singapore's garden city concept, New York's High Line Park, and other cities' green corridors and park networks are exemplary applications of innovative green infrastructure. These projects illustrate how green infrastructure can enhance the quality of life for urban residents while promoting ecological balance and economic development in cities.

Definition and Classification of Green Infrastructure

Green infrastructure is defined as a series of natural or quasi-natural elements that work together to provide ecological services to cities, promoting social welfare and economic growth. These elements include, but are not limited to, green roofs, green walls, rain gardens, urban wetlands, and community gardens. Green roofs can be divided into intensive and extensive types based on the density of vegetation and the complexity of maintenance (Zhang, 2004). Green walls and vertical gardens utilize the vertical space of buildings to increase urban green space. Rainwater harvesting systems collect and reuse rainwater, reducing urban flood risks and replenishing groundwater resources.

Classification of green infrastructure in buildings

Green infrastructures can be divided into two categories, horizontal greening devices, and vertical greening devices, according to the direction and location of placement (Gao, 2018). Horizontal greening includes green roofs and elevated forests, while vertical greening includes green facades, green walls, green terraces, and vertical forests (Zhang, 2004). Among horizontal greening, green roofs were the first form of green infrastructure to be applied to buildings, and are a form of roof with planting and planting bases. Depending on parameters such as the depth of the medium, the size of the roof, and the frequency of use, green roofs can be categorized into intensive green roofs and extensive green roofs. This type of green system can play an ecological role in the city, including reducing the urban heat island effect and adjusting the internal climate of buildings.

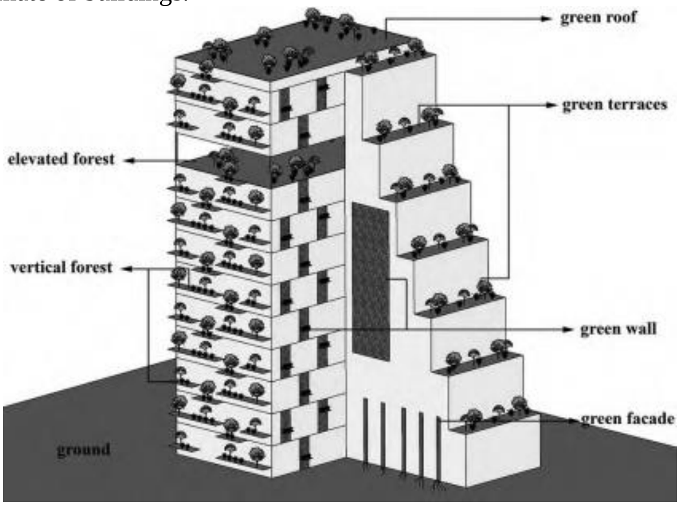

Figure 1: Location of applications in green infrastructure buildings
（Image source：https://www.archdaily.cn/cn/778006/bosco-verticale-boeri-studio?ad_source=search&ad_medium=projects_tab）

Green infrastructure, represented by green roofs and green facades, can be traced back to the sky gardens of the ancient Babylonian period. After the rise of Modernism, architects conducted various studies on green roofs and gardens that could be used by residents, and horizontally oriented green roofs were widely practiced. By the end of the 20th century and the beginning of the 21st century, green infrastructure was used to challenge the green facade as a new urban element to improve the micro-environment in the production of new buildings as well as in the restoration of old ones. Furthermore, the conservation of industrial heritage culture and the revitalization and urban renewal of industrial landscapes play a crucial role in achieving sustainable and prosperous growth in modern communities (Yi & Golnoosh, 2022).

KEY COMPONENTS OF GREEN INFRASTRUCTURE

Green infrastructure's key components, such as green roofs, walls, and rainwater harvesting systems, each play a critical role in urban sustainability and require detailed discussion and careful planning.

Green Roofs

The design of green roofs must take into account the load-bearing capacity of the roof structure to ensure it can support the weight of the soil, plants, and additional elements like walkways or seating areas (Sun, 2023). Waterproofing and drainage systems are essential to prevent water damage to the building and to ensure excess water can be effectively managed. The selection of plants should be based on their ability to thrive in the roof's specific conditions, including the depth of the growing medium, exposure to sunlight, and local climate adaptability. Intensive green roofs, which support a wide variety of plant life, offer significant ecological and recreational benefits, such as enhanced biodiversity, improved insulation, and amenity spaces for occupants. However, these roofs require more frequent maintenance and higher initial investment. In contrast, extensive green roofs, with their lower maintenance needs and cost-effectiveness, are favored for their simplicity and the benefits they provide in terms of reducing heat island effect and managing stormwater runoff.

Green Walls

Green walls, also known as living walls, introduce vertical greenery to building facades. The design of green walls must consider the structural integrity of the wall to support the weight of the plants and the hydroponic or soil-based systems used (Lu, 2016). Irrigation systems must be carefully planned to ensure even distribution of water and nutrients to the plants, which may vary with seasonality and plant species. Aesthetic considerations are also paramount; the design should complement the existing architecture and provide visual harmony with the surrounding urban landscape. Green walls contribute to improved air quality, noise reduction, and aesthetic enhancement of urban spaces.

Rainwater Harvesting Systems

The design of rainwater harvesting systems involves assessing the catchment area for collecting rainwater, which could come from rooftops or other surfaces. The storage capacity must be sized appropriately to handle the volume of water collected during peak rainfall events (Zhang, 2022). Filtration and treatment technologies are necessary to ensure the collected rainwater is suitable for its intended use, whether for irrigation, toilet flushing, or even potable uses after proper treatment. The reuse strategies for harvested rainwater should be clearly defined, taking into account local water demand and opportunities for integration with existing water systems.

In summary, the detailed discussion of green infrastructure components highlights the multifaceted considerations inherent in their design and implementation. Each component, from green roofs to walls and rainwater harvesting systems, must be carefully planned to address technical, environmental, and aesthetic challenges. By doing so, these green infrastructure elements can significantly contribute to the sustainable development of urban environments, enhancing their resilience, live ability, and visual appeal.

SELECTED CASE STUDIES

This study delves into a series of representative cases of green infrastructure, highlighting the renowned Bosco Vertical residential project as a prime example. Located in Milan, Italy, Bosco Vertical was designed by architect Stefano Boeri. The project has gained international acclaim for its innovative concept of vertical forests, where the exterior walls of the building are enveloped by a multitude of plants, aiming to create an eco-friendly living environment.

Table 1: Information about Bosco Verticale

Feature/Data Point	Description/Value
Project Name	Bosco Verticale (Vertical Forest)
Location	Porta Nuova area, Milan, Italy
Building Type	Residential Towers
Architect	Stefano Boeri Architects
Tower Heights	80 meters and 112 meters
Total Number of Trees	800 trees
Plant Species	480 large trees, 300 small trees, 15,000 perennials/ground cover plants, 5,000 shrubs
Vegetation Area	Equivalent to 30,000 square meters of woodland and undergrowth
Urban Footprint	3,000 square meters
Building Function	To limit urban sprawl, providing greenery equivalent to 50,000 square meters of single-family houses
Facade Features	Large staggered and overhanging balconies (about 3 meters deep), porcelain stoneware finish, incorporating the typical brown color of bark
Seasonal Plant Variation	Multi-colored cyclical and morphological changes, creating a rainbow landmark effect in every season
Awards	2014 International Highrise Award from Deutsches Architekturmuseums in Frankfurt 2015 CTBUH Best Tall Building in the World from the Council on Tall Buildings and Urban Habitat at Chicago's IIT
Plant Maintenance	"Flying Gardeners" team, using mountaineering techniques, annual pruning and plant checks
Irrigation System	Centrally monitored system, using filtered effluent from the towers
Animal Habitat	About 1,600 species of birds and butterflies, an outpost for spontaneous flora and fauna recolonization in the city

Notes:

- The data in the table is organized based on the provided information, reflecting the ecological, social, environmental, and economic impacts of the Bosco Verticale project.
- The project not only provides rich ecological benefits, such as a habitat for biodiversity and improved microclimate, but also has received internationally recognized awards, becoming a symbol of the city.
- The selection and distribution of plants consider aesthetic and functional criteria to adapt to the direction and height of the facades, ensuring the ecological benefits and visual appeal of the building.

- Maintenance and greening operations are managed at the condominium level to maintain the balance between humans and plants, with regular pruning and plant checks carried out by a specialized team.

Innovative Design and Technical Implementation

The Bosco Vertical project exemplifies the fusion of architecture and nature, pushing the boundaries of urban habitat design. Each tower of the Bosco Vertical is a living testimony to how green infrastructure can be integrated into the very fabric of residential buildings. The design incorporates a variety of plant species that are native or adapted to the local climate, ensuring the resilience and sustainability of the green facades. The technical implementation involves complex irrigation systems that are both energy-efficient and reliable, ensuring the survival and growth of the plants despite the challenging vertical environment.

Environmental Benefits

The environmental benefits of Bosco Vertical are manifold. The dense vegetation on the building's facades provides insulation, reducing the need for artificial heating and cooling and thus lowering the building's energy consumption. Additionally, the plants absorb carbon dioxide while releasing oxygen, contributing to improved air quality in the urban environment. The presence of vegetation also helps to mitigate the urban heat island effect, as the plants provide shade and transpire water, lowering the ambient temperature.

Impact on Residents' Quality of Life

The Bosco Vertical project has had a profound impact on the quality of life for its residents. Living in close proximity to nature has been linked to reduced stress levels and improved mental well-being (Du, 2006). The green spaces offer a serene environment that buffers residents from the hustle and bustle of city life. Moreover, the presence of green infrastructure encourages a more active lifestyle, with residents being more likely to engage in outdoor activities and social interactions within their community.

Plant Selection and Maintenance Management

The selection of plant species in Bosco Vertical was carefully considered to ensure they could thrive in the vertical environment and contribute to the overall ecosystem services. The plants were chosen for their adaptability to the local climate, resistance to wind, and ability to flourish with the automated irrigation system. Maintenance management is a critical aspect of the project, with a dedicated team responsible for the upkeep of the green facades. This includes regular checks on plant health, pruning, and replacement of any deceased flora (Yusuf & Manteghi. et al, 2021).

Adaptability to Local Climate and Culture

The Bosco Vertical project demonstrates a high degree of adaptability to the local climate and culture. The design takes into account Milan's climate, choosing plants that can withstand the seasonal variations. Moreover, the project has become a cultural symbol, reflecting the city's commitment to environmental sustainability and innovation. It has inspired other cities and developers to explore similar green infrastructure projects, showcasing the potential for vertical forests in urban landscapes worldwide.

The Bosco Vertical case study provides a comprehensive insight into the practical application of green infrastructure in urban settings. It highlights the potential of innovative design, the importance of environmental considerations, and the significant impact on residents' quality of life. As urban populations continue to grow, projects like Bosco Vertical offer a viable model for integrating green infrastructure into cityscapes, promoting ecological harmony and enhancing the well-being of urban dwellers.

This detailed exploration of Bosco Vertical and similar cases sets a benchmark for future green infrastructure projects, emphasizing the need for creativity, technical proficiency, and a deep understanding of local contexts. It is through such projects that we can envision a future where urban environments are not just places of concrete and steel but are also habitats rich in greenery and life.

PROBLEMS WITH GREEN INFRASTRUCTURE IN HUMAN HEALTH IMPACT STUDIES

Large-scale green infrastructures can provide positive social benefits by lowering local temperatures, reducing air pollution, and mitigating conflicts between urban development and natural ecology (Gao, 2018).

At the same time, some data in the literature suggest that green infrastructure may affect indicators of chronic disease morbidity and mortality. In cities, the distribution of green infrastructure affects the number of respiratory diseases in children. The health impacts of green infrastructure in these studies lacked direct and clear quantitative indicators, and there was no suitable system for evaluating their effects. When data were obtained in the studies, the period over which the data were available was small, making it difficult to establish comparisons over a long period (Sun, 2023).

In health impact studies, researchers often focus on large, urban-scale green infrastructure. These large-scale green infrastructures tend to refer to specific tree benefits, such as extensive vegetative cover, canopy shading, or traditional parks, rather than more localized green infrastructures that speak directly to building interventions, such as green wall systems, green facade systems, and rooftop green roofs that are attached to the building envelope.

There is a lack of research on the health impacts of green infrastructure, as represented by green roofs and green walls. These green facilities have different characteristics in different categories and are difficult to characterize systematically. At the same time, these green infrastructures are often small in scale, affecting only the people in and around the building, and it is difficult to measure the health impacts of these facilities (Lu, 2016).

In terms of mental health, small-scale green infrastructures placed between or within buildings had a positive impact on users and residents. With green infrastructure such as green roofs, vertical forests, and green walls, many green spaces can be created between buildings. These green spaces can be flexibly located in all parts of the building, making green gardens easily accessible to users in every area. These green gardens can be used to calm the users and have a positive effect on stress relief, mood stabilization, and physical and mental well-being. However, there is a lack of reasonable quantitative criteria for validating the psychological healing effects of green infrastructure.

ECOLOGICAL AND ECONOMIC BENEFITS OF GREEN INFRASTRUCTURE

Ecological Benefits of Green Infrastructure

In addition to the healing effect on the occupants, green infrastructure also has a regulating effect on the ecosystem. Bosco Vertical is a residential building with extensive green infrastructure, as shown in Figure 2, and the building in Milan has been certified by Leadership in Energy and Environmental Design for its extensive use of vertical forests as part of its green infrastructure. The building was expensive to construct and maintain. For the plants in the building to grow properly, the owner had to pay a large amount of money to customize a special irrigation system and observation equipment. For day-to-day maintenance and use, the operator needed to hire a special team of horticulturists to care for and prune the trees in the building to ensure that the occupants of the residential building had a normal living experience. These horticulturists are specially trained for this unique building and are required to work at heights during routine maintenance, as shown in Figure 3. From the support systems to the training of the professionals, Bosco Vertical's use of green infrastructure like vertical forests may seem like a good way to save energy, but it comes at a high additional cost.

Figure 2: Bosco Vertical
（Image source：https://www.archdaily.cn/cn/778006/bosco-verticale-boeri-studio?ad_source=search&ad_medium=projects_tab）

Figure 3: Landscaper working at heights
（Image source：https://www.archdaily.cn/cn/778006/bosco-verticale-boeri-studio?ad_source=search&ad_medium=projects_tab）

In addition, not all buildings with green infrastructure will achieve the desired ecological impact. The materials used in the construction and use of green infrastructure have an impact on the greening of a building throughout its life cycle. The environmental burden of green facade systems varies considerably depending on the material used, e.g., the use of more stainless-steel support systems can be more environmentally burdensome. Measures can be taken to reduce the environmental burden of some green facade systems, thereby reducing their energy consumption. For example, when designing green curtain wall systems, more water- and electricity-saving irrigation systems can be used, and appropriate plants and planting ratios can be selected according to the actual climatic environment of the site.

Economic Benefits of Green Infrastructure

Choosing locally appropriate green infrastructure can greatly enhance its ecological benefits throughout its life cycle. In their quest for advanced green and energy-efficient technologies and specific aesthetic effects, some owners and designers have transported special equipment from far away. The transportation process often incurs high costs and carbon emissions. When the equipment reaches the end of its useful life and needs to be replaced, it will impact the surrounding environment if it is not properly disposed of at the end-of-life stage. Considering the whole life cycle, the overall ecological and economic benefits of these green infrastructures are greatly reduced, and the cost savings of using some of the equipment far exceeds the total cost of construction, maintenance, and disposal of the equipment. Therefore, when selecting green infrastructure in the design phase, designers must prioritize locally available materials and equipment, and actively use local technologies and facilities.

Therefore, in-depth design of green infrastructure systems needs to consider the entire life cycle of the equipment, prioritize recyclable and reusable materials, and arrange for waste and recycling procedures before construction and after design. Moreover, Haruna and Manteghi et al. (2021) demonstrated that the integration of BIM technology in green building design can enhance the sustainability of construction projects and mitigate their environmental effects.

Green infrastructure is a flexible and versatile green building technology, and the use of different technologies for different environments can enhance the benefits of green infrastructure, but there is still a lack of emphasis on localization. Scholars need to work more closely with local communities to develop assessment tools that can be adapted to the context of urban development planning. Ideally, assessment tools should take into account all aspects of the city's characteristics. Each type of green infrastructure has its characteristics, aesthetic potential, and maintenance needs, and should be selected taking into account the characteristics of the building and the climate of the site (Zhang et al., 2022). Green infrastructure should not just be a decoration in the external space of the building, but when improving the image of the building facade, green curtain walls, green roofs, etc. should maximize the green benefits and achieve energy-saving effects, to maximize the economic benefits for the users.

GREEN INFRASTRUCTURE AND URBAN CONFLICTS

Green infrastructure, which consists of natural plants, is a growing aesthetic symbol. However, it has several difficulties when trying to be incorporated into the modern constructed environment. Therefore, effective planning and administration are crucial. Peng et al. (2023) conducted a study that highlighted the benefits of integrating qualitative and quantitative methodologies in analyzing building design risks. This approach enhances the theoretical foundation of risk management in construction projects. Green infrastructures can bring significant visual character to a building's exterior, transforming the cityscape and enhancing urban aesthetics while creating energy-efficient and environmentally friendly buildings. The 26-storey EDITT building in Singapore, designed by architects T R Hamzah and Yeang, has won awards for eco-design, and Ali et al. argue that the use of extensive green terraces is environmentally beneficial as it increases local biodiversity and restores ecosystems (Ali & Kheir, 2012). However, in the opinion of Tabb et al., the use of green infrastructure in the building is "a tendency of the architectural order and tectonic system to dominate the natural system in a large, rigid and unnatural way".

While the widespread use of green infrastructure in architecture is largely due to its environmental restorative effects, little research has examined the aesthetic preferences of city dwellers for green infrastructure and how underlying cultural and historical factors may influence perceptions of other urban natural systems (Dut et al., 2006). Loder used a phenomenological methodology to study office workers in a North American city. Some of the residents did not recognize green roofs as a natural form of construction, but still felt relaxed and calm, and the aesthetics of the city's previous sense of control conflicted with the targeted ecological image. The new landscape created by the green plants growing on top of the buildings is a great visual shock to the residents who are used to the bare surfaces of the buildings in the city. This disparity can lead to a blurred response to the natural areas of the city. As an emerging green space paradigm, green roofs lack the symbolic meaning of mountains and forests, and designers are keen to mimic natural environments. Loder's study is limited to green roofs as a type of green infrastructure, and there is limited research on whether people feel the same conflict with other types of green infrastructure (Loder, 2014).

CONCLUSION

As a new green building technology, green infrastructure has great potential for development. Nowadays, there are still many challenges to be solved to maximize the use of green infrastructure. As one of the solutions to the problems of nature and urban development, green infrastructure needs to be developed in a balanced way in terms of health benefits, ecological benefits, and economic benefits. In addition, a good management and evaluation system is also an important way to optimize the application of green infrastructure.

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