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Application of Vertical Greening Systems in Noise Reduction for Tropical and Subtropical Municipal Infrastructure

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Abstract. Vertical greening systems (VGS), as a newly emerging green infrastructure in recent years, have attracted significant attention in high-density tropical and subtropical cities. This article reviews the application of vertical greening systems in municipal infrastructure, focusing on the functional nature of ecological noise reduction. This article first introduces the technical classification and current status analysis of VGS, including green facades and live plant walls. Next, the environmentally friendly planting substrate, the acoustic characteristics of plant noise reduction, and the synergistic noise reduction between the two were analyzed. It also explores the practical effects of VGS in improving urban environments, noise reduction and sound absorption, and promoting sustainable development by combining application cases from Singapore and Hong Kong. At the same time, this paper summarizes the current challenges faced by VGS in terms of construction costs, long-term maintenance, and long-term noise reduction, and proposes future development directions such as eco-friendly materials, optimized plant combinations, and intelligent management technologies to enhance application value and long-term environmental benefits. Overall, vertical greening systems have good ecological noise reduction potential in tropical and subtropical regions and are an important direction for promoting sustainable green urban development.

Keywords: Vertical greening system, Ecological noise reduction, Sustainable urban development, Tropical and subtropical cities

1. Introduction

High-density urbanization has brought rapid socioeconomic growth, but it has also exacerbated environmental noise pollution from construction, transportation, and commercial activities. This has made environmental noise a major source of pollution affecting residents' quality of life and polluting the natural environment.

The main traditional urban noise reduction measures are engineering methods such as sound barriers, soundproof walls, and building soundproofing materials. These methods have certain limitations, as they are limited in terms of large land footprint, single landscapes, and ecological functions in high-density cities. To address these issues, vertical greening systems can utilize building facades, bridges, and other vertical urban spaces in high-density urbanization. Existing studies have shown that vertical greening systems can alleviate urban heat island effects, reduce

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building energy consumption, and improve air quality, among other ecological benefits. For example, in the case of Hong Kong's public housing, vertical greening systems can reduce air conditioning energy consumption by about 16% in summer [1]. Zhao et al. analyzed related research from 2000 to 2022, showing that research on vertical greening systems has gradually expanded from building greening to urban ecosystem services [2]. Meanwhile, the acoustics of vertical greening systems are gradually developing. Research shows that the system influences sound wave propagation through the vibration and scattering reflections of plant leaves, combined with the porous sound absorption of the growth substrate, which also has a certain attenuating effect on traffic noise [3]. Therefore, vertical greening systems are not only a way to improve urban landscapes but are also gradually becoming a technical means for noise control and ecological environment enhancement in urban infrastructure.

For tropical and subtropical regions, due to year-round high temperatures and humidity, high urban building density, traffic congestion, and limited available green spaces, there are significant challenges in controlling the urban natural environment and noise. Continuous high temperatures, high humidity, and heavy rainfall affect plant growth and canopy structure, increase the moisture content of the system's plant growth substrate, alter the internal pore structure and acoustics, and cause significant fluctuations in noise reduction and sound absorption performance. In this environment, the module materials used in the system need to maintain long-term durability and drainage, while also requiring high maintenance. Therefore, vertical greening systems applied in high-temperature and high-humidity environments require not only good noise reduction but also careful consideration of material durability and stability to ensure long-term effective noise reduction.

Based on the above background, this article takes vertical greening systems in tropical and subtropical cities and regions as the research object, reviews the main types and current applications of vertical greening systems, and focuses on the impact of eco-friendly materials, plant configuration, and vertical greening structures on acoustic noise reduction. Combining typical cases from Singapore and Hong Kong, summarizing application characteristics, existing problems, and future development directions and trends, it provides theoretical references for the construction of green municipal infrastructure and urban noise control in tropical and subtropical cities and regions.

2. Overview of vertical greening systems (VGS)

2.1. Main technical classification and acoustic research progress of VGS

The current vertical greening system is mainly divided into two types of technologies: green facades and living plant walls. The characteristics of green facades mainly rely on climbing plants and hanging plants growing on the exterior of buildings and steel grid structures. The roots of plants are usually underground or in planting containers. This structure is relatively simple, with low construction costs and less construction difficulty. The characteristics of living plant walls are greatly different, forming modules of plants, growth substrates, supporting structures, and irrigation systems, and constructing them on vertical walls of buildings at different heights. According to different planting methods, living plant walls are further divided into two modes: modular living plant walls and continuous living plant walls.

Structural differences lead to significant acoustic differentiation. Kulak Dalkilic and Yazicioglu used impedance experiments to study and evaluate the acoustic performance of green facades, modular living plant walls, and continuous living plant walls [4]. Results show that the modular living plant wall has the highest weighted sound absorption coefficient ($\alpha w = 0.75$), demonstrating

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strong sound absorption. The continuous live plant wall has the highest weighted insulated sound volume (Rw = 16 dB), demonstrating better sound transmission barrier performance. The study also showed that setting up air chambers between living plant walls and building walls to form a double-layer structure can further improve the acoustic performance of the system, especially with the potential to improve low-frequency sound absorption [4]. In contrast, the overall acoustic performance of the green facade is relatively lower compared to the two living plant walls (as shown in Table 1).

Table 1. Comparison of acoustic performance of different vertical greening system construction forms [4]

System construction form	Main experimental results	Applicable scenarios
Green facade	Relatively low acoustic performance	Relatively low acoustic performance
Modular living plant wall	αw=0.75, Best sound absorption performance	αw=0.75, Best sound absorption performance
Continuous living plant wall	Rw=16Db, Best sound insulation	Rw=16Db, Best sound insulation performance
Double layer structure	Set up an air layer to improve low-frequency sound absorption	Setting up an air layer to further improve low-frequency sound absorption performance

2.2. Vertical greening systems in municipal applications

With the development of vertical greening systems, their application has gradually shifted from building facades to municipal infrastructure, and various forms have been developed according to different scenarios. In the field of traffic noise and urban greening, the main forms are road green sound barriers, green public building facades, green retaining walls, green urban boundary fences, and elevated bridge greening (as shown in Table 2).

In the above application forms, the combination of vertical greening systems and transportation infrastructure has high research value. Previous studies have shown that building facades and green sound barriers can reduce the propagation characteristics of traffic noise and thus lower road noise by verifying the common effects of plants, growth substrates, and system structures. The road sound barrier near Tsing Tsuen Bridge in Hong Kong also uses embedded plant walls, reflecting the practical application of vertical greening combined with bridge road infrastructure. This shows that vertical greening systems have expanded from single application scenarios to include roads, elevated bridges, retaining walls, and city boundaries, providing multiple types of reference applications for managing urban noise caused by high-density urbanization.

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Table 2. Main application forms of vertical greening system in municipal infrastructure

Municipal application form	Main carrier	Common VGS forms	Main Features
Green noise barrier for roads	Roads and expressways	Modular plant wall/green barrier	Form a continuous vertical green interface
Greening of elevated bridges	Bridge piers, bridge sides, and elevated structures	Modular VGS/Climbing Greening	Utilize vertical space of transportation facilities
Greening of retaining walls	Road retaining walls and slopes	Green facade/modular design	Combined with engineering retaining structures
Exterior facade of public buildings	Exterior wall of a building	Green facade/living plant wall	Combined with the building envelope structure
Urban boundaries and walls	Walls and road boundaries	Climbing greening/modularization	Combined with the building envelope structure

3. Ecological noise reduction and environmental protection material performance and noise reduction effect in vertical greening systems

3.1. Modular lightweight sound-absorbing growth matrix material performance

The noise reduction of vertical greening systems is the result of the combined action of plant coverage area, planting substrate, plant canopy, and porous composite material structure. In recent years, with the development of green building and low-carbon construction concepts, research has shifted from traditional plant greening noise reduction to plant combinations and composite inorganic acoustic effects, emphasizing the impact of environmentally friendly materials and plant combinations on the adaptability and sound absorption capabilities of vertical greening systems in humid and hot environments.

The growth matrix is an important component of modularity, a necessary substance for plant growth, and also an important component of sound absorption effect. The pore structure, composition, and breathability of the materials all affect sound wave propagation and energy consumption. Experimental research by Oquendo-Di Cosola et al. shows that the matrix is the component in the module that has the greatest impact on sound absorption performance, and its sound absorption coefficient increases with frequency, exhibiting typical characteristics of porous sound-absorbing materials [5]. Existing studies show that polyporous eco-friendly materials can dissipate sound wave energy and improve absorption of medium- and high-frequency noise by increasing the propagation path of sound waves within the material. Bakker, Lugten, and Tenpierik specifically reviewed the acoustic mechanisms of porous materials for traffic noise control. The matrix essentially belongs to porous sound absorbers, and its main acoustic mechanism is viscous heat dissipation [3]. When sound waves enter interconnected pores, air moves near the hole walls and generates friction, and the sound energy is eventually converted into heat and dissipated. Among these, the distribution, number, and size of the pores, as well as the internal connections of the material, are important factors determining sound absorption performance.

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In recent years, modular planting substrates have gradually adopted lightweight and eco-friendly substrates such as coconut shell, coconut husk, biochar, and vermiculite. Experiments have shown that lightweight porous environmentally friendly materials such as coconut shell fiber, biochar, and vermiculite have varying degrees of potential for sound absorption. For example, coconut shell fiber composite sound-absorbing panels have a maximum absorption coefficient of 0.92; Wibawa et al. found that biochar-PVA composites have a maximum sound absorption coefficient of 0.21 at about 440 Hz; the sound absorption coefficient of the vermiculite-fused waste paper green composite material experiment in 2025 is about 0.89, and the noise reduction coefficient (NRC) is 0.72 [6, 7]. The results show that the internal structure of the porous material can increase the propagation path while promoting acoustic energy consumption, showing great potential as a modular planting substrate for vertical greening systems. Improving plant growth and resource utilization provides a more sustainable material selection demand for green noise reduction projects in municipal infrastructure.

3.2. Material-based application of plant acoustic characteristics

Plants themselves are a crucial part of achieving VGS acoustic effects, with leaves, branches, and canopies forming a complex sound-absorbing and noise-reducing system. They can absorb, reflect, and scatter sound waves, block their propagation, and thus reduce noise. Previous studies have shown that there are significant differences in sound absorption performance among different plant species. Leaf size, plant coverage, and canopy structure all affect the effectiveness of sound absorption and scattering. Larger blades and coverage areas generally have better noise reduction effects [3]. Related experiments show that plant planting density also affects sound absorption performance; for example, boxwood with a density of 16 pots/m² showed better acoustic absorption in the test plant. Meanwhile, compared to a single plant action, the joint operation of plants and porous growth substrates can produce better sound absorption effects: In the experiment, the sound absorption coefficient of the individual fern layer was below 0.30, when combined with a 10cm porous substrate, the sound absorption coefficient can reach 0.70–0.80 at around 400Hz, and above 1200 Hz, close to 0.90, this indicates that the joint cooperation between plants and growth substrates can further enhance the comprehensive sound absorption performance of VGS [3]. Therefore, in tropical and subtropical regions, it is necessary to combine local plant species with ecological adaptability and acoustic performance to enhance the ecological benefits of VGS.

3.3. Coupling effect of humid and hot climate conditions on material noise reduction performance

Based on the climate characteristics of high temperature, high humidity, and high rainfall density in tropical and subtropical regions, the growth substrate is in a state of absorbing and evaporating water, and changes in the substrate's moisture content affect its sound absorption and noise reduction performance. Bakker et al. pointed out that after the porous sound-absorbing matrix absorbs moisture, it will cause the internal particle materials to expand, thereby reducing the internal pore size of the material [3]. Material pores are the main factor in reducing sound waves; excessive moisture content lowers the scattering frequency of sound waves within the matrix, thereby affecting noise reduction effectiveness.

Shushunova et al. conducted systematic acoustic tests on plant walls with different water content states and found that, on dry walls without plants, the weighted noise absorption coefficient αw is 1.00, while on wet walls with a moisture content of 60%–70%, αw drops to 0.50, indicating that

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increased substrate moisture reduces system sound absorption and noise reduction efficiency [8]. Another study, Oquendo-Di Cosola et al., shows that the growth matrix accounts for 80%-90% of the sound absorption contribution of modular systems, and the pore size expands with humidity, affecting mid-to-high frequency sound absorption [6].

Therefore, in high-temperature and high-humidity environments, the sound absorption and noise reduction performance of the growth substrate in vertical greening systems enhances or diminishes with the changes in water absorption, evaporation, and drying.

4. Case study on technology integration of typical high-density cities in tropical and subtropical regions

4.1. Case 1: Singapore - integration of infrastructure "gardenization" and modular lightweight plant walls

Singapore, as one of the first countries and regions to adopt the vertical greening system globally, has incorporated VGS into a key strategy for green building and eco-city development. Represented by Hort Park, the facade is landscaped, and vertical gardens deeply integrate plants with the building facade. Experiments have been conducted on various vertical greening system structures, and the study shows that noise reduction is not limited to plant leaves but is also achieved through combined operations involving plants, porous growth substrates, and system structures. Plant leaves scatter and absorb some sound waves, while the porous growth substrate repeatedly reflects sound waves through its internal pores, thereby dissipating sound wave energy and reducing their frequency. At the same time, the modules and walls form an air layer that changes the propagation of sound waves. Wong et al. compared eight systems under different conditions, and the results showed that each system structure produced different effects, with some structural combinations achieving noise reduction close to 10dB [9]. The results indicate that the noise reduction effect of the Singapore case comes from the synergistic effect of the system structure, rather than the effect of a single plant.

4.2. Case 2: greening of municipal retaining walls and elevated bridges in the urban environment of Gaomi Canyon, Hong Kong, China

Hong Kong has long been plagued by limited land resources, high building density, high building temperatures, and excessive refrigeration noise. Therefore, vertical greening systems have gradually become the main method to address these problems. Through studying the actual measurements of public residential buildings in Hong Kong, an 8.22 m^2 VGS is installed on the building's facade, and under sunny conditions, the surface temperature difference between the green walls and the building walls reaches 1-8°C. A more efficient data point is that during the hottest months of August and September in Hong Kong, VGS can reduce the overall power consumption of air conditioning by up to 16%. Experiments have shown that vertical greening systems can promote cooling, energy conservation, and emission reduction [9]. In another study on high-density streets in Hong Kong cities, VGS can reduce street temperature by approximately 1.06 ℃. Additionally, the combined effect of plant structures and planting substrates reduces road noise. For example, Hong Kong's Sau Mau Ping South Estate uses vertical sound barriers composed of reinforced concrete and vegetated panels, reducing overall traffic noise by about 4–8 dB, and approximately 3,200 residential units thus meet road traffic noise standards [10]. The above case illustrates that vertical greening systems have sustainable effects in reducing traffic noise and energy conservation in high-density cities.

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5. Challenges and future prospects of vertical greening noise reduction technology

5.1. Stability of noise reduction due to high humidity and high heat

Multiple research studies indicate that vertical greening systems can produce significant noise reduction and cooling changes, but there are still many challenges that need to be addressed before they can be widely applied. The noise reduction performance of existing vertical greening systems is affected by plant combinations and planting substrate materials under high humidity and heat conditions. Bakker et al. , combining more than 40 VGS acoustic studies, stated that the main noise reduction effect of VGS is the porous growth matrix, with effective sound-absorbing and noise-reduction frequencies mainly above 200 Hz. The material's porosity, pore size, pore density, and air resistance are all key factors affecting acoustic energy consumption [3]. Under conditions of high temperature, high humidity, and dense rainfall, an increase in the moisture content of the planting substrate can affect the internal sound wave scattering and reflection of porous materials, increase air flow resistance, and reduce sound wave absorption capacity. Recent studies show that in living plant walls, the growth substrate accounts for about 80%–90% of the absorption volume, and the plant structural layer about 5%–20%, indicating that the porous sound-absorbing substrate contains too much water, which affects the overall system's noise reduction and sound-absorption status [3]. Therefore, for cities with high temperatures and humidity such as Singapore, Hong Kong, and Kuala Lumpur, VGS should focus on controlling the permeability and moisture content of the planting substrate materials, as well as the stability of the materials and their durability under specific climatic conditions, in order to maintain long-term good noise reduction and sound absorption performance.

5.2. Future research and technological development trends

At present, there is a lack of systematic research on VGS under various global climate conditions in terms of technology, and emphasis should be placed on developing and designing system types that can adapt to different climate conditions. How to accurately quantify and optimize the combination ratio of plant canopy and specific porosity matrix for traffic noise in specific frequency bands, making the outlook forward-looking. Experiments by Attal and Dauchez show that both the thickness of the plant layer and the density of plant leaves affect sound wave reflection, scattering, and sound propagation in the 100–1000 Hz range [11]. Dalkılıç and Yazıcıoğlu further found that the weighted sound absorption coefficient of the modular living plant wall is $\alpha w=0.75$, and the weighted sound insulation for continuous living plant walls is Rw = 16dB. Simultaneously adding an air layer to form a double-layer structure of an air layer and a planting substrate layer can simultaneously improve low-frequency noise [4]. The second drawback is the lack of a unified measurement standard system for system acoustics. Bakker et al., after synthesizing over 40 studies on VGS acoustics, pointed out that there are significant differences in experimental and scale ranges as well as measurement methods, making data comparison very difficult [3]. Therefore, in the future, it is necessary to establish a unified evaluation standard and strengthen long-term testing under different seasons and temperature conditions. Technically, the focus should be on developing substrate characteristics such as porosity, high-temperature and humidity resistance, and lightweight quality. At the same time, by integrating plant canopy structure, plant planting density, plant combination and modular planting, as well as the coordinated airflow layer and intelligent irrigation, it enhances efficiency in sound absorption and noise reduction, energy conservation and emission reduction, and maintenance.

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6. Conclusion

This project summarizes the technical classification and application scenarios of vertical greening systems, and also analyzes the effects of modular planting growth matrix materials and plant characteristics on sound absorption and noise reduction based on previous research data. Research shows that VGS, through its modular structure and the synergistic effect of planting substrate and plant combinations, can not only effectively reduce traffic noise but also save energy and mitigate the urban heat island effect, thereby improving environmental quality.

Through case studies in Singapore and Hong Kong, vertical greening systems can effectively reduce traffic noise and building facade temperature in high-density cities with high heat and humidity, thereby reducing air conditioning cooling time and achieving energy-saving and emission reduction effects. Meanwhile, the lack of a standardized evaluation system for measurement and noise reduction remains a major reason limiting further adoption.

Overall, vertical greening systems are green infrastructure facilities that combine ecological and social benefits, promoting sustainable development in tropical and subtropical regions. In the future, it is necessary to establish standardized evaluation systems, strengthen research and development of environmentally friendly planting substrates, and optimize plant configurations and improve maintenance plans to reduce costs, combined with modular design and intelligent management technology, to enhance the long-term operational effectiveness of the system. Provide sustainable solutions for urban noise reduction, energy conservation, emission reduction, and mitigation of urban heat island benefits.

In summary, this study believes that vertical greening systems have good potential for ecological noise reduction applications in green infrastructure construction in tropical and subtropical regions, becoming the main direction for future high-density urban development.

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