NOISE POLLUTION REDUCTION AND CONTROL PROVIDED BY GREEN LIVING SYSTEMS IN URBAN AREAS

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Abstract: *Greening the building envelope is innovative technology in architecture that can regain losses of a natural environment in dense urban areas. Implementation of green living systems, greening horizontal surfaces with intensive and extensive green roofs or using vegetation in vertical greening systems for façades is a strategy that provides ecological, economic and social benefits and it is a sustainable solution for improving the environmental balance of cities limiting the major negative effects of urbanization providing better comfort at both building and urban level. The potential to provide external and internal sound insulation due to their high mass and absorption through the surface, reducing and control of noise pollution in urban areas, was investigated trough various studies. There are several situations in which noise reduction due to green living systems' sound absorption should be considered important, such as buildings near to roads, rail or air traffic noise sources. The configurations of the systems, substrate thickness, and vegetation layer, are important factors affecting the sound absorption and sound propagation properties of these systems.*

This review paper presents findings from different research conditions and approaches, to explore the importance of green living systems considering the impact on noise mitigation and acoustic aesthetics of the environment.

Keywords: GREEN LIVING SYSTEMS, GREEN ROOF, GREEN WALL, ACOUSTIC INSULATION, NOISE POLLUTION

1. Introduction

Rapid urbanization increases the energy problem of cities and decreases the proportion of spaces dedicated to green infrastructures due to new building developments amplifying the pollution problems. Greening the building envelope is innovative technology in architecture that can regain losses of a natural environment in dense urban areas. Implementation of green living systems is a strategy that provides ecological, economic and social benefits and it is a sustainable solution for improving the environmental balance of cities limiting the major negative effects of urbanization.

In addition to the creation of a pleasant environment, the aesthetic visual and acoustic impressions, green living systems offer several substantial benefits in comparison to the conventional building envelope. Main environmental benefits that green living systems (GLS) can achieve are energy consumption reduction, a decrease of the urban heat island effect, reduction of carbon footprints, air pollution mitigation, reduction in storm-water runoff and improvement of a storm-water quality, reduction in interior noise levels, noise absorption [1]. Depending on the types of plants and soils, a GLS can provide a natural habitat for animals, insects, and plants and can increase the biodiversity of an urban area [2].

Noise is understood as a sound that is loud, unpleasant, unexpected, or undesired. The primary reasons to decrease noise is to avoid direct damage, but also to increase comfort whilst sleeping, working and socializing. Noise can also cause economic problems through decreased efficiency amongst employees as well as lowered property values due to less demand. GLS have the potential to provide external and internal sound insulation due to their high mass and absorption through the surface, reduce and control of noise pollution in urban areas. In terms of acoustic benefit, vegetation, in general, affects the sound field in urban environments through mechanisms. When a sound wave impinges on the vegetation and is then reflected back sound absorption and diffusion occur; and when a sound wave is transmitted through the vegetation sound level reduction occurs.

2. The Green Living Systems

Living architecture is the integration of the living, organic systems characterized by green walls and green roofs, with the inorganic and lifeless structures that have come to dominate modern architecture. By combining nature and built areas in their designs, architects and urban planners can respond to serious human health and welfare issues and restore the environmental quality of dense urban areas. Green living systems are not only the solution for the new designs. Retrofitting existing buildings by altering the buildings' surficial properties can reduce buildings' energy and address air and noise pollution.

2.1. The green living walls

Green wall technologies may refer to all forms of vegetated wall surfaces. Two major categories can be identified: Green Facades and Living Walls.

The Green facades are a type of green wall system in which climbing plants or cascading groundcovers are trained to cover specially designed supporting structures (Fig 1. left). Rooted at the base of these structures, in the ground or in intermediate planters.

Fig. 1 *The Green Façade Singapore Changi Airport Terminal 3, Singapore, Singapore (left),The Living Wall Europa Congress Palace Convention Center, Vitoria-Gasteiz, Spain (right)*

The Living wall systems are composed of prevegetated panels, vertical modules or planted blankets that are fixed vertically to a structural wall or frame (Fig. 1. right). These panels can be made of plastic, expanded polystyrene, synthetic fabric, clay, metal, and concrete, and support a great diversity and density of plant species.

2.2. The green living roofs

Green roof construction mimics in a few centimeters what normal soil does in a couple meters. The green roof accomplishes the natural balance through several layers depending on its complexity.

The model of the green roof consists of three main components: structural support, a soil layer, and foliage layer. The structural support includes all the layers between the inner plaster and the drainage layer or filter layer. In most cases, the structural layer is considered as a single layer with constant properties. The drainage layer provides water for upper layers in relatively small space and with light weight. The soil layer, or the growing medium, is complex with the solid phase (organic and mineral material), the liquid phase (water) and the gaseous phase (water vapor and air).

The growing medium, filter, drainage layer and protection layer act to support plants and protect lower levels. The foliage layer (canopy) is composed of the leafs and the air within the leafs, and its characteristics depend on the plant selection.

There are two main classifications of green roofs: Extensive Green Roofs (EGR) and Intensive Green Roofs (IGR)

Extensive Green Roofs are lightweight in structure with a thinner substrate and feature succulent plants like sedums that can survive in harsh conditions (Fig. 2. left).

Fig. 2 *EGR, Bridgepoint Active Healthcare, Toronto, ON (left), IGR, Aventura Optima Plaza, Aventura, FL (right)*

Intensive Green Roofs may require irrigation during dry periods having a thicker soil layer than extensive ones. Because of their thicker soil, these roofs require greater structural support (Fig. 2. right). IGR allow a greater variety and size of plants such as shrubs and small trees but have higher initial costs and maintenance.

3. Evaluation of green living systems on noise pollution reduction and control

The acoustical performance of green living systems involves two different aspects: the outdoor noise absorption and the insulation of indoor environments from outside noise. In street canyons and urban environments, sound propagation through the urban fabric from noisy areas into quiet zones is influenced by a variety of geometrical parameters such as street width and building height, as well as the acoustic characteristics of the materials used in the building envelope. This means that there is important potential for reducing acoustic waves diffracting over building since the envelope is most often made of rigid materials, thus can be improved using the vegetation.

From the previous studies concerning the sound interception provided by vegetation it is known that it can reduce sound levels in three ways:

- Sound can be reflected and diffracted (scattered) by plant elements. Trunks, branches, twig and leaves have the different influence.
- Sound can be absorbed by plant elements. Mechanical vibrations of plant elements caused by sound waves lead to energy dissipation by converting sound energy to heat. There is also a contribution to attenuation by thermo-viscous boundary layer effects at vegetation surfaces.
- Sound levels can be reduced by the destructive interference of sound waves. The presence of soil can lead to destructive interference between the direct contribution from the source to the receiver and a ground-reflected contribution. The presence of vegetation leads to an acoustically very soft soil. This effect is often referred to as the acoustical ground effect or ground dip.

Regarding the urban noise attenuation by vegetation, in their research [3] Dunnet and Kingsbury stated that the hard surfaces of urban areas tend to reflect sound rather than absorb it and that green roofs can absorb sound, with both the substrate and plants contributing. The substrate tends to block lower sound frequencies, whereas plants block higher frequencies.

3.1. Evaluation of green living walls on noise pollution reduction and control

In the study [4], where only the direct transmission of sound through the modular green wall was considered, two different standardized laboratory tests were conducted. The main results were a weighted sound reduction index R_w (which is a value that is expressed as a single number (UNE-EN ISO 717-1)) of 15 dB and a weighted sound absorption coefficient α (defined as the proportion of sound energy that is absorbed by the material from an incident sound) of 0.40. The sound absorption coefficient remained more constant between 0.35 and 0.51, reflecting a good performance of the green wall not only at low frequencies but at high frequencies as well. The capacity of the green wall to reduce airborne noise, which is expressed by the R coefficient, was lower than the other constructive solutions (Fig. 3.)

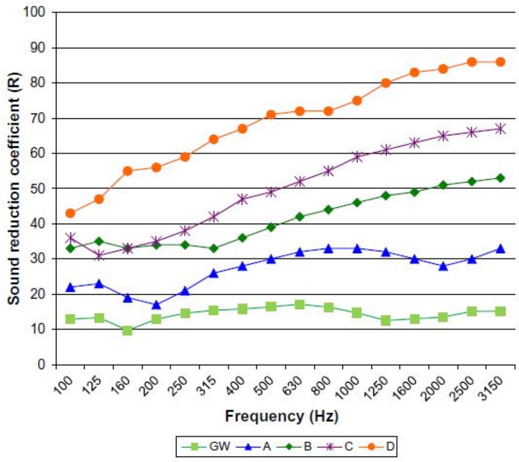

Fig. 3 *Sound reduction coefficient (R) comparison between the green wall (GW) and common constructive solutions: A. Thermal double glazing (6-12-6), timber frame, B. Brick, 100 mm thick, no finish. C. Lightweight aggregate blockwork 215 mm thick with plaster finish both sides. D. Two leaves of 12.5 mm + 19 mm plasterboard on metal studs, separated by 250 mm cavity with 100 mm mineral wool [4].*

Researchers concluded that green walls have significant potential as a sound insulation tool for buildings but that some design adjustments should be performed.

An acoustical measurement campaign around a site, located in Cergy, in the Val d'Oise department, near Paris, France, hosting a green wall was carried out to highlight its potential effectiveness in reducing noise pollution in its environment [5]. Measurements showed a decrease in overall sound pressure levels (dBA) generated by road traffic as a result of setting up the green wall on the site. Acoustic gains remained moderate and ranged from 0.6 to 2.5 dBA depending on the measurements day. In the middle frequencies, 400 - 2500 Hz, acoustic gains were moderate (between 0 and 6 dB depending on the configuration and the one-third octave band concerned) with maximum efficiency for configurations where the source was distant from the receiver. These can be attributed to acoustic absorption due to the planting substrate. At high frequencies, 3150 to 20000Hz, except for close source/receiver configurations, acoustic gains were substantial (between 0 and 10 dB depending on the configuration and the one-third octave band concerned), where a scattering phenomenon caused by the foliage of the development also comes into play.

The interesting paper described the construction of a vertical indoor greenery system (VIGS) on the north side of a wall and assessed the noise mitigation that resulted from the use of a vegetation-covered wall face [6]. Sound level measurements were recorded in dBAs. The source content provided a continuous level sound from 55 to 115 dBA with different voices from adults and children. The average decrease in dBAs was between 2% with the frequency weightings equivalent to the sound frequencies that the human ear perceives, and 3% for the with the frequency weightings equivalent to the sound frequencies perceived by the human ear, excluding extreme frequencies. This may indicate up to a three-fold reduction in energy caused by the green wall. In the case of noise that lasted longer than 1s, which can be considered the most troublesome for human sensitivity, there was a sonic mitigation of 6% to 8% for the selected frequency using those two weightings, respectively.

3.2. Evaluation of green living walls on noise pollution reduction and control

Transmission loss (TL) is a measure of how much sound energy is reduced in transmission through a single or multi-layered partition. The green roof as a series of finite layers impedes sound energy as it transmits from the exterior environment through each layer of the system to the interior of the building. Architectural acoustics is most often concerned with the sound transmission in the frequency range of 125−4000 Hz.

The empirical findings on the sound transmission loss of green roofs suggest that the use of green roof technologies may be optimized to increase transmission loss and ameliorate the coincidence effect. The field testing [7] conducted on two 33 m^2 extensive green roofs indicated an increase of 5 to 13 dB in TL over the low and mid frequency range, 50 Hz to 2000 Hz, and 2 dB to 8 dB increase in TL in the higher frequency range above the reference. It was highlighted that green roofs would provide a higher TL than the additional ceiling element and improve TL throughout the full architectural frequency range, specifically desirable in residential occupancies developed below aircraft flight paths.

The sound transmission loss of a reference roof (conventional type) and two green roofs, identical with the only difference in the depth size of the substrate (75 mm for GR1 and 150 mm for GR2), was measured [8]. The analysis revealed that the increase of TL through GR1 at different frequencies was less consistent while the respective increase of TL through GR2 was more reliable. The findings also demonstrate that deep green roof increased the transmission loss from 5 dB to 13 dB at low and mid frequency bands 50–2000Hz, and of less than 6 dB at higher frequencies.

The Finite-Difference Time-Domain Method was used to study sound propagation over a green roof in an urban situation [9]. Sound propagation between adjacent city canyons was considered, and the focus was on the reduction of the sound pressure level in the non-exposed canyon due to the presence of a green roof. Numerical calculations were conducted for both intensive and extensive green roofs, showing that an important reduction of the sound pressure level in the shielded canyon could be achieved, compared to a rigid roof. In the case of an extensive green roof, there was a strong dependence on the substrate layer thickness; a maximum reduction of 10 dB at the octave band of 1000Hz was found. A good overall efficiency was observed near the maximum layer thickness as found in practice for this type of green roof. For intensive green roofs, the influence of the substrate layer thickness was limited. Both extensive and intensive green roofs significantly reduced the sound levels in the non-exposed canyon. At low frequencies, effects were minimal since the substrate impedance was large. For a typical intensive green roof, more than 6 dB was gained at the octave band of 1000Hz, relative to a fully rigid roof, when the green fraction of the roof was 0.8. In this research, a linear relationship between the green roof effect and the fraction of the roof covered with green, and the slopes increase with the octave band centre frequency was confirmed.

Laboratory study [10], with a series of measurements of Sound Pressure Level (SPL) in the semi-anechoic chamber were carried out to demonstrate the effect of green roof systems on noise abatement at street levels, considering diffracted sound waves propagating through a low profiled structure. For green roof systems, trays which are composed of the Zinco substrate with a depth of 100mm and low growing vegetation were applied. To verify the acoustic effects of the green roof system, four experimental parameters were considered, including the structure, area and position of the green roof system, and the type of vegetation. The experimental results on the effect of the structures of the green roof trays suggest that the trays can disperse sound energy from diffracted sound waves effectively and further theoretical approach could be made to design this to an optimal condition. With different areas of the green roof system, a noise reduction of over 10 dB was observed. The effect on noise reduction was gradually increased with increasing number of rows of the trays. The experimental results with the pruned leaves show that dense leaves have positive effects on noise mitigation mainly at high frequencies above 4000Hz. In terms of the acoustic effects of the position of the green roof system, the measurement results suggest they sensitively affect the pattern of noise reduction at different frequency ranges.

In Flanders, Belgium, measurements were performed just before and after placement of the green roof, with an identical source-receiver configuration in both situations [11]. The results showed what can be expected from current green roof practice for sound diffracting over it, for various building configurations. The first situation involved a building extension with a green roof where the sound was forced to be diffracted over it (shearing sound propagation over the green roof) before reaching a façade or window (single diffraction). The second situation aimed at achieving a silent zone at a non-directly exposed façade while the source was in an adjacent street canyon. In the latter, the green roof was modeled on the main part of the building (double diffraction). Measurements showed that green roofs may lead to consistent and significant sound reduction at locations where only diffracted sound waves arrive. Among the single diffraction cases, acoustic green roof improvements exceeding 10 dB were found, over a wide frequency range. This improvement was measured for a propagation path interacting with the green roof of only 4.5 m. The presence of shearing waves over the green roof (near parallel sound propagation to the roof), and sufficient substrate thickness seemed to be important to have such large positive effects. For the double diffraction cases, positive effects were measured over the full frequency range from 50Hz to 10kHz, at the two fully shielded receiver heights considered in the experiments. Effects seemed to be less-frequency dependent than for the single diffraction cases, and a case with positive effects up to 10 dB was found. It was concluded that small substrate thickness and/or the presence of vegetation was positive for higher frequencies, while for low-frequency noise reduction a larger substrate thickness was needed.

Experimental data on acoustical performances on the sound absorption of the green roof systems were evaluated and discussed in the study [12]. Three green roof systems had been experimentally tested measuring their sound absorption coefficients at normal incidence: extensive green roof (Sample A), semi-intensive green roof (Sample B) and common soil (Sample C). The sound absorption depends on the angle of incidence of the acoustical waves on the surface of the material.

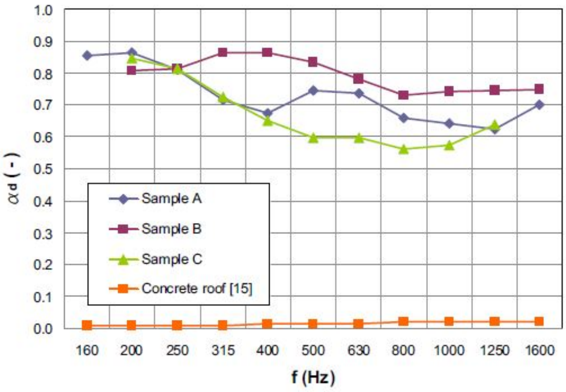

Fig. 4 *Comparison of curves for sound absorption coefficient at random incidence [12].*

The value of the normal incidence absorption coefficient □α_0 is an important parameter in applications when the sound absorbing material is very close to the sound source. For green roofs relatively far from the sound source, such as a building close to an urban road, the most important parameter results is the random incidence sound absorption coefficient α_d. The diagram showed (Fig. 4.) the high advantage in the use of green roofs compared to traditional roof techniques. Results confirmed that, generally, sound absorption of green roofs was higher than the absorption estimated for concrete traditional roofing, demonstrating the effectiveness of the solution. It must be noticed that sound absorption coefficients at random incidence $\alpha_{d,w}$ and $\alpha_{d,m}$ presented higher values than sound absorption coefficients at normal incidence $\alpha_{0,w}$ and $\alpha_{0,m}$ (Tab. 1).

Table 1: *Weighted and average sound absorption coefficients at normal and random incidence [12]*

Roof types	$\alpha_{0,w}$	$\alpha_{0,m}$	$\alpha_{d,w}$	$\alpha_{d,m}$
Sample A	0.45	0.75	0.64	0.76
Sample B	0.60	0.80	0.54	0.80
Sample C	0.40	0.60	0.44	0.63
Concrete roof	0.00	0.00	0.02	0.02

4. Conclusion

In street canyons, the amount of sound energy propagating over rooftops from noisy sides to quite sides is mainly determined by the height and width of buildings, and also materials used in building envelope. Green living roofs on the top of buildings can be assumed as absorbers especially for diffracted sound waves between parallel streets. Thus, in the aspect of acoustic advantages, green living systems have been regarded as an important structure to reduce noise pollution in urbanized areas such as street canyons.

Green living systems can absorb sound, with both the substrate and vegetation contributing. The substrate tends to block lower sound frequencies, whereas vegetation blocks higher frequencies. Growing mediums used in green living systems are highly-porous, and allow acoustic waves to enter the medium, which is a necessary property of a sound absorbing material. Due to a large number of interactions between the waves and the solid phase of the substrate attenuation occurs. Also, the typical substrates are known for their high water retention capabilities. The volume of the substrate particles will increase largely by absorbing water, leading to a decreased porosity of the substrate layer. Furthermore, the presence of water reservoirs or the use of rock-wool mats to further enhance water retention is not optimal from the acoustic viewpoint, knowing that porous materials and outdoor ground surfaces can be largely affected by the presence of water usually leading to a decreased sound absorption. On the other hand, such layers could largely improve these aspects under dry conditions. When vegetation is present on building envelope the effectiveness of absorption can be greatly enhanced since there are multiple reflections. In build-up areas the absorption and diffusion effects are also useful for reducing the negative effect of reflections from the ground that often occur in outdoor sound propagation.

The configurations of the systems, substrate thickness and vegetation layer, are important factors affecting the sound absorption and sound propagation properties of these systems. That should be taken into consideration if the green living systems are designed as a means of noise pollution reduction and control.

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