Acoustic insulation capacity of Vertical Greenery Systems for buildings

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Abstract

Vertical Greenery Systems (VGS) are promising contemporary Green Infrastructure which contribute to the provision of several ecosystem services both at building and urban scales. Among others, the building acoustic insulation and the urban noise reduction could be considered. Traditionally vegetation has been used to acoustically insulate urban areas, especially from the traffic noise. Now, with the introduction of vegetation in buildings, through the VGS, it is necessary to provide experimental data on its operation as acoustic insulation tool in the built environment. In this study the acoustic insulation capacity of two VGS was conducted through *in situ* measurements according to the UNE-EN ISO 140-5 standard. From the results, it was observed that a thin layer of vegetation (20-30 cm) was able to provide an increase in the sound insulation of 1 dB for traffic noise (in both cases, Green Wall and Green Facade), and an insulation increase between 2 dB (Green Wall) to 3 dB (Green Facade) for a pink noise. In addition to the vegetation contribution to sound insulation, the influence of other factors such as the mass factor (thickness, density and composition of the substrate layer) and type of modular unit of cultivation, the impenetrability (sealing joints between modules) and structural insulation (support structure) must be taken into account for further studies.

Keywords: *Acoustic insulation, vertical greenery systems, green walls, green façades, green infrastructure, ecosystem services, urban noise reduction, buildings.*

1. Introduction

The acoustical environment in and around buildings is influenced by numerous interrelated and interdependent factors associated with the building planning – design-construction process. The architect, the engineer, the building technologist, and the constructor all play a part in the control of the acoustical environment. With some fundamental understanding of basic acoustical principles, how materials and structures control the sound, many problems can be avoided altogether or, at least, solved in the early stages of the project at greatly reduced cost. "Corrective" measures are inevitably more costly after the building is finished and occupied [1].

On the other hand, Green Infrastructure (GI) is a successfully tested tool for providing ecological, economic and social benefits through natural solutions for the built environment. Compared to single-purpose grey infrastructure, GI has many benefits, offering sometimes an alternative or being complementary to standard grey solutions. Generally, GI could be defined as a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services. It incorporates green spaces (or blue if aquatic ecosystems are concerned) and other physical features in terrestrial (including coastal) and marine areas. On land, GI is present both in rural and urban settings [2]. Among the multiple eco-system services provided by GI in the built environment, such as runoff control, energy savings, support to biodiversity, roof materials protection, etc., it is said that some acoustic insulation at building scale whilst also some city noise reduction at urban scale are provided [3].

The types of physical features that contribute to GI are diverse, specific to each location or place and very scale-dependent. On the local scale, biodiversity-rich parks, gardens, green roofs and green walls, ponds, streams, woods, hedgerows, meadows, restored brownfield sites and coastal sand-dunes can all contribute to GI if they deliver multiple ecosystem services. Between those GI features, Vertical Greenery Systems (VGS) and Green Roofs for buildings are promising contemporary construction systems which contribute to the provision of ecosystem services both at building and urban scales [3].

Some authors highlight the contribution of VGS and green roofs on the improvement of urban environment by means of the reduction of noise. Thus, while hard surfaces of urban areas tend to reflect sound rather than absorb it, green construction systems can absorb sound, with both substrate and plants making a contribution, the former tending to block lower sound frequencies and the latter higher ones. However, few case studies and even less experimental data were found in the literature regarding to the actual contribution of these systems to noise reduction [4, 5]. In addition, regarding the acoustic insulation effects of vegetation when it is incorporated in buildings, previous studies usually consider the contribution of green roofs to acoustic insulation, while references to vertical green systems are scarce.

An interesting example of the use of vegetation in order to improve the acoustic insulation of a building is the Almeida Theatre in London (Figure 1) by Haworth Tompkins studio. To achieve the required level of sound insulation, the roof and gables of the building were turfed in Sedum, a hardy cactus-like plant. The resulting pitched roof garden, full of wild flowers in the centre of a busy urban block, has become a local landmark [6].

Figure 1. Building greenery as acoustic insulation. Almeida Theatre. London

Traditionally large masses of vegetation to acoustically insulate different urban areas, especially from the traffic noise, have been employed. In this regard, vegetation is attributed with some acoustic noise reduction up to 8 dB, and occasionally more [7]. Recent studies, relating to road traffic noise shielding by vegetation belts, already stressed that for an equal amount of biomass per unit surface area, there is a preference for shrubs, either low shrubs (0.5 m) or higher shrubs (2 m). In these studies it was concluded that a 2 m-high shrub zone with a length of 15 m, for a total above-ground dry biomass of 4 kg/m^2, gives an average road traffic noise insertion loss of 4.7 dBA for a light vehicle at 70 km/h at typical ear heights when referenced to sound propagation over grassland. Relating to the acoustic insulation properties of green systems, it is said that vegetation can reduce sound levels in three direct ways. First, the sound can be reflected and scattered (diffracted) by plant elements, such as trunks, branches, twigs and leaves. As a second mechanism there is the sound absorption by vegetation. This effect can be attributed to mechanical vibrations of plant elements caused by sound waves, leading to dissipation by converting sound energy to heat. As a third mechanism, could be also mentioned that sound levels can be reduced by the destructive interference of sound waves by the soil layers presence [8].

Studying the sound propagation through vegetation other authors concluded that the effect of a belt of vegetation on sound propagating through it is highly frequency dependent so that at frequencies below 1 kHz the vegetation is almost transparent whereas above 1 kHz attenuation results from the interaction of scattering and absorption [9].

Figure 2. Road traffic noise shielding by vegetation belts

From these previous studies about green belts of vegetation emerges the conclusion that the most influential factors on their operation for sound insulation are multiple, such as the kinds of species, the green screen dimensions, its shape as well as its location with respect to the noise source.

Furthermore, on these studies one worked with the assumption that plant screens thickness can be around few meters, while in the case of VGS for buildings, it will be difficult to achieve these thicknesses. Consequently, it is very important to know what could be the contribution to the sound insulation from plant element when working with thin vegetation layers, usually less than a meter.

Thus, the incorporation of vegetation to buildings through the use of green infrastructure, i.e. VGS and green roofs, with acoustic insulation purposes, implies the definition and control of multiple factors relating not only to the vegetation layer but also to the support structure and the materials used.

Therefore, with the incorporation of vegetation to buildings, i.e. urban Green Infrastructure through Green Roofs and VGS, it is important to determine whether these systems can provide acoustic insulation and noise control. Here it should be taken into account the fact that there are multiple types of VGS and therefore, just as happens when they are used for thermal insulation purpose, the acoustic insulation capacity may be also typology dependent. Thus, the kind of system used must be considered when comparing research results [10].

A classification for VGS has been established previously showing significant differences between systems both in terms of the support structure as well as in reference to the plant species used. Generally speaking VGS can be classified into two clearly differentiated groups, the Green Façades and the Living Walls [11]. Green façades are Green Vertical Systems in which climbing plants or hanging port shrubs are developed using special support structures, mainly in a directed way, to cover the desired area. Green façades can be divided into three different systems. Traditional green façades, where climber plants use the façade material as a support; double-skin green façade by means a light structure that serves as support for climbing plants, with the aim of creating a double-skin or green curtain separate from the wall; and perimeter flowerpots, when as a part of the composition of the façade, hanging shrubs are planted around the building to constitute a green curtain. Living walls are made of geotextile felts and/or panels, sometimes pre-cultivate, which are fixed to a vertical support or on the wall structure. The panels and geotextile felts provide support to the vegetation formed by upholstering plants, ferns, small shrubs, and perennial flower, among others.

In view of this classification, and considering the possibility of sound insulation provision from VGS, it must be considered the fact that in the case of Green Façades the insulation can been provided by the vegetation layer, whereas in the case of Green Walls other factors must be taken into account, such as the substrate, the module box, the geotextile felts, etc. depending on the system used. In addition and for any case, Green Façades and Green Walls, it must be also considered the impact on the acoustic behaviour of the different types of support structure.

From the results of the scarce previous experimental studies about the acoustic behaviour of VGS no strong conclusions could be drawn due to both the different experimental methodologies as well as the different construction systems evaluated. It must be highlighted that only one *in situ* experiment was found, being the others laboratory studies with small samples or simulations.

Wong et al. [12] evaluated the soundproofing potential of different VGS by means of the *in situ* measurement of their provided insertion loss. The insertion loss was defined as the difference, in decibels, between two sound pressure level (SPL) which are measured at the same point in space before and after an object is inserted between the measurement point and the noise source. Hence, “before an object is inserted” refers to the control wall while “after an object is inserted” refers to the VGS. Their difference in

SPL is the insertion loss due to the addition of VGS. The most important conclusions were that those systems that use substrate in the structure showed a stronger attenuation of the insertion loss for middle frequencies, due to the absorption effect of substrate (reductions around 5 to 10 dB). In addition, a smaller attenuation is observed at high frequency spectrum due to the scattering effect of greenery (reductions from 2 to 3.9 dB). Moreover, in this study it could be confirmed that absorption coefficient increases with higher frequencies as well as with greater greenery coverage. On the recommendations of this study the authors emphasize that, to further advance the research, acoustics studies of VGS should be performed on actual building façades in an attempt to reveal more acoustics insight.

Other studies deal with more detail the sound insulation properties of substrates and plants used in VGS rather than with the whole system performance. Thus Van Renterghem et al. [13] in a numerical study highlight that usually used substrates for green walls have high porosity and low density and consequently show a complex acoustic behaviour. Moreover, the presence of water inside the substrate could strongly affect its absorption properties so that in the extreme case, when the porous medium is fully water-saturated, similar effects as for a rigid material could be expected. On the other hand, according to Horoshenkov et al. [14], the absorption coefficient of plants is controlled predominantly by the leaf area density and the angle leaf orientation. On the other hand, light-density soils exhibit very high values of acoustic absorption whereas the absorption coefficient of high-density clay base soil is low.

From these studies, the need to homogenize the way of studying the acoustic behaviour of VGS can be deduced. In this regard, is necessary to consider that ISO 140 describes the standards to measure the buildings and construction elements acoustic insulation.

In a recent previous study [15], the potential of a Green Wall as passive acoustic insulation system for buildings was evaluated under laboratory conditions. The studied parameters were the airborne sound insulation and the measured sound absorption in reverberation room. The tests were performed according to UNE-EN ISO 10140-2 standard. The calculated weighted sound reduction index was R_w = 15dB, and the correction terms were C_{tr} = -1 dB for traffic noise and C = -1 dB for pink noise. These values, although lower than those for other common construction systems, are very promising. From the measurement of the sound absorption in the reverberation room according to UNE-EN ISO 354 standards, the calculated value of the weighted sound absorption coefficient was $\alpha_w = 0.40$. Comparing these results with those of previous studies, it can be concluded that the introduction of the green wall specimen into the reverberation room implies a reduction in the reverberation time (from 4.2 to 5.9 in this study), highlighting and quantifying the sound absorption capacity of this construction system. But, the values obtained in the laboratory are characteristic of that material or construction system under controlled conditions, and only gives an idea about the potential sound insulation capacity, but not about its final performance in real conditions, i.e. when the material or system is a part of a building.

Consequently, it is important to highlight the necessity to perform *in situ* measurements of the acoustic insulation capacity of these new construction systems. Specifically, in the case of building facade elements, the reference standard for measuring their acoustic behaviour is the UNE-EN ISO 140-5 *Acoustics. Measurement of sound insulation in buildings and of building elements. Part 5: Field measurements of airborne sound insulation of façade elements and façades.*

Therefore, this paper aims to provide *in situ* measurements of acoustic insulation capacity of two VGS according to the UNE-EN ISO 140-5 standard. For this purpose a representative construction system of Green Walls group and another representative one of Green facade type were chosen. The selected Green Wall was an existing one, which is currently in the market, and which was previously tested in laboratory in order to measure its acoustic performance under controlled conditions [16]. As for the Green Façades, a simple Double-skin Green Facade typology was built and tested.

2. Materials and methods

The experimental set-up consists of two cubicles (Figure 3) located in Puigverd de Lleida, Spain, with the same external dimensions (3 x 3 x 3 m). Their bases consist of a mortar base of 3 × 3 m with crushed stones and reinforcing bars. The walls present the following layers from inside out (Figure 4): gypsum, alveolar brick (30 × 19 × 29 cm), and cement mortar finish. No additional insulation was used in the walls of these cubicles. The roof is a conventional flat roof (precast concrete beams and ceramic floor arch 25 cm) with 8 cm of extruded polystyrene insulation layer above, concrete relieved pending formation of 2%, double waterproofing membrane, and finished with a single layer of gravel of 7 cm thickness (Figure 4) [17,18]. The only difference between the two cubicles used in the present research is the use of a different VGS located in the west, south and east façades of each of these cubicles. Thus, one of them was finished with a Green Wall, while the other one was finished with a Double-skin Green Façade.

Figure 3. Experimental set-up in Puigverd de Lleida, Spain

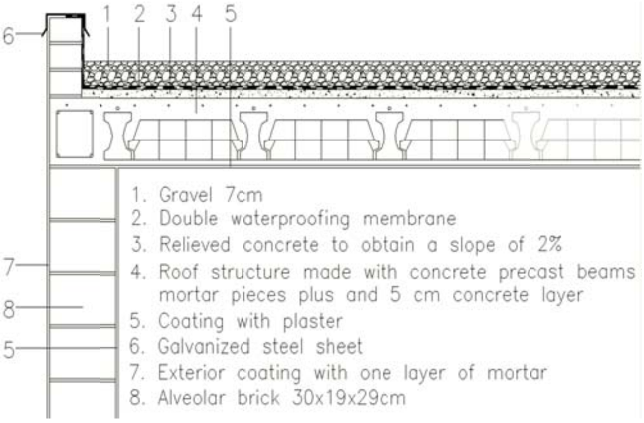

Figure 4. Construction section of the cubicles used in this experimentation

The Green Wall used was a pre-cultivated modular-based system based on recycled polyethylene modules [16]. The module consists in a closed box made with a 3 mm thickness recycled plastic which has recycled polyethylene hooks that hold them to the supporting structure (Figure 5). The module is filled with coconut fibre substrate. The support structure consists of stainless steel tubes where the modules are adjusted hanging on the hooks so that they cannot be drawn perpendicular to the wall, preventing theft. The irrigation system responds to fertigation techniques so that, by adjusting the nutrient solution, plant growth can be controlled, reducing the irrigation requirements. Each module was designed to hold 24 small shrubs. Usually native plants were used, which are well adapted to the local climate and hence they have low water needs. In this study two different plant species were used, *Rosmarinus officinalis* and *Helichrysum thianschanicum*.

Figure 5. Green Wall made with polyethylene modules, coconut fibre substrate and native shrubs

On the other hand, the Double-skin Green Façade was made with a simple 2 mm wire mesh parallel to the cubicle façade wall, located 25 cm away by means of metallic supports anchored to the wall (Figure 6). The plant species used in this green façade was Boston Ivy (*Parthenocissus Tricuspidata*), which is a climber plant well adapted to the Mediterranean Continental climate.

Figure 6. **Double-skin Green Façade made with wire mesh and Boston Ivy**

In order to study the acoustic insulation potential of these two VGS the reference standard UNE-EN ISO 140-5 *Acoustics. Measurement of sound insulation in buildings and of building elements. Part 5: Field measurements of airborne sound insulation of façade elements and façades* has been followed.

With the aim of observing the effect of vegetation on the acoustic performance, data collection was repeated during two different periods. Thus, in the first phase the acoustic insulation in low vegetation conditions was determined, and the second measurement took place in abundant vegetation cover conditions (Figure 7).

The measurements were performed with an integrating sound level-meter and a type1 CESVA analyser, model SC310. Before the measurements, the proper functioning of the computer with a sound gauge Bruer & Kjaer type 4230 (94 dB-1000 Hz) was verified. In all cases, the measurements were done by the third octave bands from 20 to 10,000 Hz.

To measure the sound insulation it is necessary to play a standard sound with a high enough and equal level in all frequency bands. To carry out this experiment, a normalized pink noise is generated, which after being amplified, it is emitted by a twelve speakers as sound source system and consequently becoming in an omnidirectional sound source.

UNE-EN ISO 140-5 standard establishes the procedure for *in situ* measurements of airborne sound insulation for facade elements and façades. As stated in this standard, for such kind of measurements both traffic noise and speaker can be used as sound source. In this study, given the location of the cubicles in an isolated environment, the second method was chosen.

According to this standard, the noise source should be placed in front of the facade or facade element to be measured, at a distance d and with an angle of sound incidence equal to 45 ° ± 5 ° with the item. Due to the small size of the façades to analyse, 3.4 m high, it is not possible to meet this condition. For this reason it was considered appropriate the placement of the noise source at a distance of 2.3 m from the wall and at a height respect ground of 1.2 m (Figure 7). In all cases, the analysed wall was the opposite of the wall that contains the entrance of the cubicle. Thus, as the wall to be measured as the two side walls are blind walls, without doors, windows or any other opening which may favour the transmission of sound.

Figure 7. In situ acoustic measurements according to UNE-EN ISO 140-5

The measurement procedure consisted of generating a normalized noise from the omnidirectional source placed as detailed in the previous paragraph and measured the following parameters:

- The equivalent sound pressure level outside (transmitter) taking measurements in third octave bands in various positions in front of the facade to be analysed.
- The equivalent sound pressure level inside (receiver) taking measurements in third octave bands in various positions inside the cubicle.
- The level of background noise in third octave bands, measured inside the cubicle with the source without working.

Subsequently, the omnidirectional source was placed inside the cubicle and the reverberation time of the receiving room was determined. The method used was the abrupt interruption of emission.

For each frequency band, the "standardized difference of levels" $D_{2m,\,nT}$ was determined by the following expression:

$$D_{2m,nT} = L_{1,2m} - L_2 + 10 \log \frac{\boldsymbol{Tr}}{\boldsymbol{T0}} \quad [\mathrm{dB}]$$

where:

$L_{1,2m}$ is the equivalent sound pressure level measured outside (emitter) and 2m from the façade

L_2 is the equivalent sound pressure level measured inside (receiver) corrected by the level of background noise

T_r is the reverberation time measured in receiver room

T_0 is the reference reverberation time of 0.5 s value according to UNE-EN ISO 140-5 for *in situ* measurements of airborne sound insulation for facade elements and façades

The overall value assigned to the isolation of the different elements, $D_{2m,\,nT,\,w}$ (C; C_{tr}) was calculated according to the guidelines of the UNE-EN ISO 717-1 standard, where C and C_{tr} correspond to the spectral correction terms for adaptation to traffic noise and pink respectively.

3. Results and discussion

The tests results are presented in four graphic which show the standardized difference of levels $D_{2m,\ nT}$ in third octave frequency bands as stablished in the ISO 140.

A comparison between the results obtained in the first phase, i.e. without foliage, and the results from the second phase, with foliage, are shown in Figure 8.

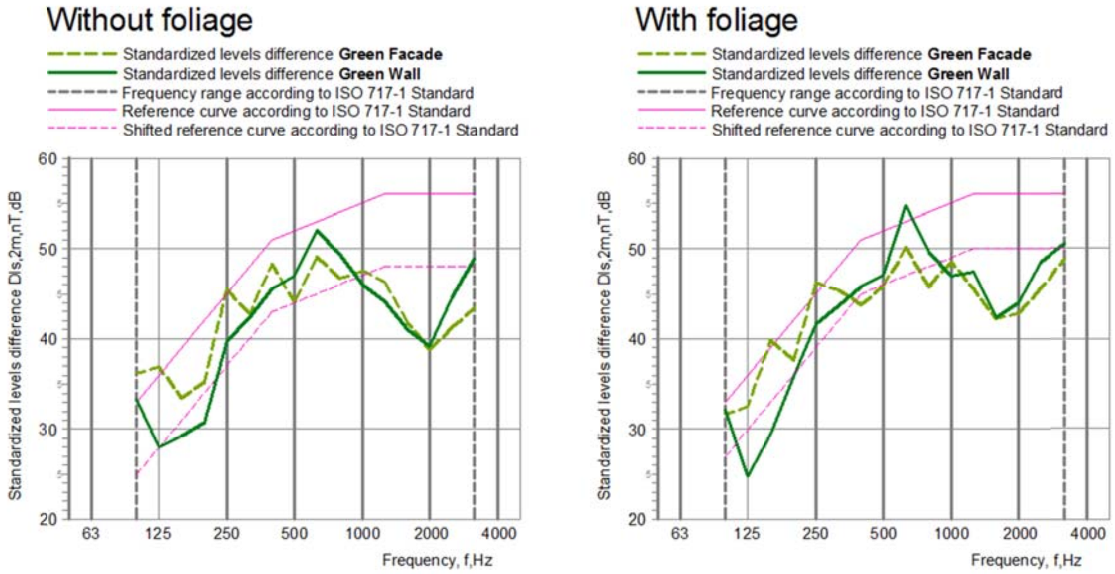

Figure 8. Standardized difference of levels D2m, nT. With and without foliage comparison

These results agree with those obtained in 2010 by Wong et al. in which the acoustic insulation capacity increases in the intermediate frequency reaching a peak around 800 Hz, due to the absorption effect of the substrate. In addition, around 2000 Hz a reduction of acoustic insulation capacity takes place which, according to the authors, is due to focusing effect of VGS. Thus, due to the periodic arrangement of greenery, reflections and scatterings may focus sound energy onto certain region near the surfaces resulting in a negative insertion loss. Finally, in the high frequencies zone the improvement of insulation acoustic capacity is due to the scattering by greenery.

Moreover, in Figure 9 the results are shown so that a comparison between the two studied systems, Green Walls and Green Façades, can be done. Again the two phases are considered, with and without foliage.

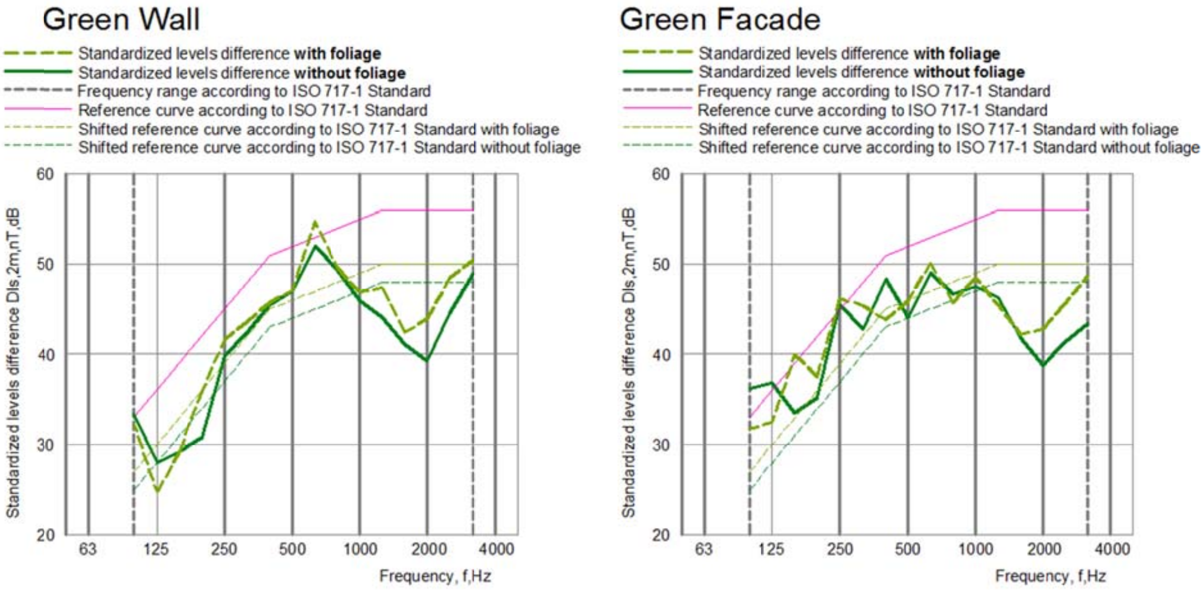

Figure 9. Standardized difference of levels D2m, nT. Green Wall vs Green Facade

This graphic show that the acoustic performance of the Green Wall and the Green Façade differed significantly throughout the frequency spectrum, in terms of the Green facade showed a profile much more irregular than the Green Wall profile, which had a much more defined. This fact reveals that the effect of the substrate on the acoustic performance is very important and it should be considered in future studies and for possible improvements of these systems.

Moreover, it can be observed that during the second phase, i.e. with vegetation, the acoustic behaviour of both systems was again different. Thus, it can see that the improvement in the sound insulation capacity for the Green Wall takes place almost throughout the profile, with special emphasis on the peak due to the substrate effect in middle frequencies, and the increment due to the vegetation effect in the high frequencies. It can be also observed that in the low frequencies the opposite effect was found, with a reduction on the insulation capacity. According to the study conducted by Wong et al. this effect may be the result of sound diffraction in low frequencies where the sound wave bends around an obstacle.

On the other hand, more variability throughout the frequency profile can be observed for Green Façade, though also improves especially at high frequencies due to the effect of vegetation.

Finally, Table 1 summarizes the single-number quantities obtained for the standardized levels difference, which is the value used to express the acoustic insulation between a room and the outdoor.

As the standardized difference of levels is a frequency dependent magnitude, the acoustic insulation capacity of a construction system always must be assessed by means of the analysis of its profile. But, in order to assess and to compare results, the acoustic insulation can be characterized by an unique value, the weighted single-number quantity, which can be identified by the subscript w (e.g $D_{2m,nT,w}$). The single-number quantity represents the value in dB, at 500 Hz of a reference curve which is shifted to fit insulation values obtained experimentally, by the method specified by the standard EN ISO 717.

Single-number quantities depend on the sound spectrum of the noise source, so they are usually accompanied by a spectral correction term (C, Ctr):

- C is the adaptation spectral term for the sound reduction index for pink noise incident or rail traffic noise, in dB. It will be used when talking about building elements and acoustic insulation between two homes. The index of insulation from pink noise is more realistic against traffic noise at high speeds, both road and rail, living activities (talking, music, radio, and TV), or noise that is generated within dwellings.

- C_{tr} is the adaptation spectral term for the sound reduction index for noise of cars and aircraft, in dB. It will be used in the construction elements and facade insulation. The normalized traffic noise spectrum gives more weight to low frequencies, allowing the gathering of more realistic noise indices against urban traffic, railway traffic at low speeds, disco music or certain industrial noises

Table 1. Standardized levels difference D2m,nT,w (dB). Single-number quantities

		$D_{2m,nT,w}$ [dB]	**Corrected value to pink noise (C**	**Corrected value to traffic noise (C_{tr})**
With foliage	**Green Façade**	**46**	**(-1) 45**	**(-3) 43**
	Green Wall	**46**	**(-2) 44**	**(-5) 41**
Without foliage	**Green Façade**	**44**	**(-2) 42**	**(-2) 42**
	Green Wall	**44**	**(-2) 42**	**(-4) 40**

As it can be seen in Table 1, no big differences between the two VGS on the soundproofing values were found, neither with nor without vegetation.

In both cubicles, the presence of vegetation implies an increase on the soundproofing of 1 dB regarding the situation without vegetation, in the case of normalized traffic noise spectrum, and 2 dB for the Green Wall and 3 dB for the Green Façade, in the case of consider pink noise.

At low frequencies (≤315 Hz) the cubicle with Green Wall presents smaller sound insulation than the Double-skin Facade Green cubicle, resulting in a single-number quantity of 41 dB, i.e. 2 dB lower than the single-number quantity for the cubicle with Double-skin Green Façade.

Although measurements about the leaf area density and the possible influence of the type of plant used on the acoustical insulation were not carried out, the differences on these results between the two systems could have been influenced by the leaves morphology, as stated Horoshenkov [14], because a broadleaf climber plant was used for the Double-skin Green Facade (*Parthenocissus Tricuspidata*), whereas two shrub species with narrow and small leaves were used for the Green Wall system (*Rosmarinus officinalis* and *Helichrysum thianschanicum*).

It is evident that these results despite being positive do not correspond to the promising results obtained in laboratory tests. As mentioned previously, in the tests carried out in order to calculate the airborne sound insulation, following the UNE-EN ISO 10140-2 standards, the measured weighted sound reduction index was Rw = 15dB, and the correction terms were Ctr = -1 dB for traffic noise and C = -1 dB for pink noise. In this study, the calculated value of the weighted sound absorption coefficient was αw = 0.40 (UNE-EN ISO 354 standards) [15].

This fact reveals that, despite it can be confirmed that a small thickness of vegetation already provides a certain acoustic insulation, the construction of VGS on the cubicles generated changes which cause a worsening on its acoustical performance when compared to laboratory experiments.

In this regard, it must be kept in mind that the improvement of a single partition is not enough to achieve a good sound insulation in a building, because the sound can find indirect ways to be transmitted. Therefore, working *in situ* the main method to improve the acoustic insulation of a building is usually to control the sound transmission, being the most important parameters to consider the mass, the impenetrability, and the structural insulation.

Regarding to the **mass**, is necessary to consider that the heavier (more mass) the partitions surrounding us have, the more difficult is that they vibrate with sound, decreasing in consequence its transmission. Therefore, it would be necessary to provide much more mass to the support structures to achieve better behaviour in front of the sound. This measure can be achieved in the case of Green Walls by improving the composition of substrates used for this purpose. Usually the substrate composition in green walls responds to plant survival necessities (i.e. the provision of water, nutrients and physical support) as well as weight constraints, but not to supply other ecosystem services such as thermal or acoustic insulation. Taking into account the thermal or acoustic insulation properties of substrate could improve the Green Wall performance as an insulating structure. This option can hardly be applied to Green Façades due to their own design, because plants usually are placed in pots at the bottom of the facade or in middle positions, being the support structure mesh or wire in front of the wall facade.

Another aspect to consider is the possibility of gaining mass in the vegetation layer, either by increasing the thickness or by using plant species with higher foliage density. That measure could be applied to both main typologies of VGS, to the Green Walls and to the Green Façades (Figure 5 and Figure 6). It should be taken into account that one of the main factors to consider when plants are used as soundproofing around the roads is just the thickness and density of green screens [7-9]. This is also according to the study conducted by Van Renterghem et al. [8], in which by studying the road traffic noise shielding by vegetation belts already highlighted the importance of the amount of biomass in the noise attenuation. Also, in the study of Wong et al. [12], one of the main conclusions was that with greater greenery coverage there is an increase in the sound absorption coefficient.

In the case of **impenetrability**, it is known that small fissures can cause big effects on global acoustic insulation. Thus, in the case of a building it is necessary to ensure the sealing of doors and windows, as well as conduits for passing tubes and cables, plugs, etc., because they can be a source of sound transmission spoiling a good acoustic insulation of the entire facade. This issue can unlikely be improved in a Double-Skin Facade system which is fully permeable and in where the whole function of acoustic insulation is provided by the vegetation layer, On the contrary, in the case of the Green Wall, the complete sealing of the joints between modules and in the façade edges would lead to an improvement on sound insulation in terms of impenetrability (Figure 5 and Figure 6).

Finally, regarding the so-called **structural insulation**, it is necessary to consider that a certain physical separation between building elements must be guaranteed in order to prevent the sound transmission. For example, the existence of a simple nail can spoil the sound insulation between two wall layers separated by an air chamber. For this reason usually it is recommended that the air chambers used in buildings should be the widest as possible and even filled with insulating material to prevent that the air acts as a bridge between the two layers.

This can be the main aspect to improve for the two analyzed VGS because in both cases, Green Wall and Double-skin Green Facade, lightweight structures anchored directly to the building facade wall were used resulting probably in the existence of acoustic bridges (Figure 5 and Figure 6).

4. Conclusions

By studying the *in situ* acoustic insulation capacity of two VGS for buildings under controlled conditions, according to the UNE-EN ISO 140-5 standard, it can be concluded that:

- In quantitative terms, a thin layer of vegetation (20-30 cm) was able to provide an increase in the sound insulation of 1 dB for traffic noise (in both cases, Green Wall and Green Facade), and an insulation increase between 2 dB (Green Wall) to 3 dB (Green Facade) for a pink noise.
- The acoustic insulation contribution from both greenery systems (scattering) in high frequencies, as well as from substrate (absorption) in the middle frequencies by Green Walls, were verified in the standardized difference of levels profiles.
- In the case of the studied Green Wall, the differences between the good results obtained in previous laboratory studies and the obtained *in situ* measurements, suggest that it is necessary to consider other factors, in addition to the vegetation, in order to improve the acoustic insulation capacity of VGS, such as the mass (thickness and composition of the substrate and vegetation layers), impenetrability (sealing joints between modules) and structural insulation (support structure).

In general it can be concluded that vegetation can really contribute to the sound insulation of the building, in the design of VGS all the factors that influence their acoustic behavior must be considered. Concerning this, studies regarding to the types of plants, the thickness of the vegetation layer, the thickness and composition of the substrate layer, the type of support structure and materials to be used, as well as to take measures to prevent transmission of sound on the early design phase (structural impenetrability and insulation) should be made.

In addition, future experiments should be made following international standards of measurement in order to compare experiments and results relating to the different VGS.

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