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Acoustics evaluation of vertical greenery systems for building walls

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ABSTRACT

After decades of fast growth, the scarcity of land in cities causes many buildings to be constructed very close to expressways, exposing occupants to serious noise pollution. In recent years, sustainable cities have found that greenery is a key element in addressing this noise pollution, giving rise to the popularity of vertical greenery systems (VGS). This research has two objectives. The first involves the study of eight different vertical greenery systems installed in HortPark, Singapore to evaluate their acoustics impacts on the insertion loss of building walls. Experiment shows a stronger attenuation at low to middle frequencies due to the absorbing effect of substrate while a smaller attenuation is observed at high frequencies due to scattering from greenery. Generally, VGS 2, 7 and 8 exhibit relatively better insertion loss. The second objective aims to determine the sound absorption coefficient of the vertical greenery system constructed in the reverberation chamber which is found to have one of the highest values compared with other building materials and furnishings. Furthermore, as frequencies increases, the sound absorption coefficient increases. In addition, it is observed that the sound absorption coefficient increases with greater greenery coverage.

1. Introduction

After several decades of fast urban growth, many big cities are densely overpopulated. The scarcity of land causes many buildings to be constructed very close to expressways or bus terminals, exposing occupants to serious noise pollution. It was found that more than 44% of the population within the European Union was exposed to road traffic noise levels over 55 dB in 2000 [1].

Cities who are aiming to create a new sustainable urban lifestyle have found that greenery is a key element in addressing this noise pollution. Urban developers are currently searching for areas to plant vegetation. Hence, the greening of the façade of building walls, known as vertical greenery systems (VGS), is gaining in popularity. The widespread use of vertical greenery systems on the numerous building walls in cities not only represents a great potential in reducing urban noises generated from traffic and machines, it is also a highly impactful way of mitigating the urban heat island effect and transforming the urban landscape.

This research has two objectives. The first involves the study of eight different vertical greenery systems installed in HortPark, Singapore to evaluate their acoustics impacts on the insertion loss of building walls. The second objective aims at determining the sound absorption coefficient of the vertical greenery system constructed in the reverberation chamber of National University of Singapore (NUS). This is a project initiated by the Centre for Urban Greenery and Ecology (CUGE) of the National Parks Board (NParks), in collaboration with the Building and Construction Authority (BCA) and NUS.

2. Literature review

Research on the acoustics performance of vertical greenery systems is limited and almost non-existent. However, the noise reduction properties of vegetation on the ground are extensively researched. In addition, significant amount of urban greenery articles published look into the acoustics performance of rooftop gardens. These two research areas provide the foundation in analyzing the acoustics performance of vertical greenery systems in an urban setting.

Scattering and ground attenuation were found to be the principal factors causing sound attenuation when random noise was transmitted over dense corn, hemlock plantation, pine stand, hardwood brush and cultivated soil [2]. Furthermore, in south-eastern Nebraska, trees are found to reduce sound level by 5–8 dB. The width of these tree belts determine the effectiveness of the sound attenuation which can reach beyond 10 dB [3].

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In another interesting experiment, branches of pine trees were brought into a small reverberant chamber to determine their sound absorption mechanism and the acoustics attenuation is found to be due to the thermoviscous absorption in the surrounding air's boundary layers [4].

In addition, sound levels from passing trains were determined to be 8–9 dB lower behind a dense, 15-year-old, 50 m wide tree belt which is made up of beeches, conifers, birches and elms, compared to grass-covered ground [5]. Similarly, several locations where road traffic noises were significant were measured and attenuations were found to be significantly higher through belts of trees and bushes when the frequency of noise went beyond 2 kHz [6].

The effect of a belt of maize on sound propagation is found to depend on frequency. For frequencies below 1 kHz, the effect is almost non-existence while for higher frequencies, noise attenuation is obtained due to the interaction of scattering and absorption [7].

Similarly, the reverberation and attenuation over a range of frequency in a pine forest ranging from a tenth of a meter to a meter deep were measured. The level of road traffic noise transmitted through is significantly lower than that transmitted over a pasture of the same depth [8].

The sound absorption coefficient of four different trees, Japanese Aucuba, Japanese cedar, Spindle tree and Sawara cypress are determined in a reverberation chamber experiment. Results showed that acoustics attenuation is independent of the leaf surface area and mainly came from the leaves instead of the truck [9].

Research found that a combination of earthen berm with a variety of plants can reduce noise by 6–15 dB and increasing the width of the plant belt can lower the noise level [10]. Correspondingly, eight plantations in India coalfields were investigated and the average trend of total noise attenuation at different depths of the green belt was evaluated to compute the minimum desired thickness for different locations [11].

Furthermore, the noise reduction effect of 35 evergreen tree belts was investigated. Negative and positive logarithmic relationships were found between visibility and the width, length or height of tree belts when compared with relative attenuation respectively [12]. Likewise, the visibility, height, and width of the tree belt, the height of noise receiver and source as well as the distance between noise source and receiver from six tree belts were studied to develop a multiple regression model showcasing the relative order of importance of these five parameters in comparison with relative attenuation [13].

Lastly, the acoustic absorption coefficients of grass surfaces with grass blades measuring 0.03 and 0.10 m in both wet and dry soil conditions are determined based on ISO 13472-1 using an acoustic impulse response [14].

In recent years, the acoustics research on vegetation starts to focus its attention to the rooftop gardens which are gaining in popularity. Comparing the transmission loss between a roof with and without rooftop garden using the Schroeder method found an addition noise reduction of 5–20 dB due to the presence of rooftop garden [15].

In another rooftop garden experiment, it was determined that an extensive green roof is able to increase the transmission loss by 5–13 dB within frequency range of 50–2000 Hz. For higher frequencies up to 4 kHz, additional 2–8 dB loss in transmission is experienced [16].

Using finite difference marching forward in the time with the Zwikker and Kosten method, the highest noise attenuation peak of 10 dB is found with respect to an acoustically rigid roof in the octave band of 1 kHz and a 0.15–0.20 m thick substrate is determined to provide good acoustics properties [17]. Similarly, the finite difference time-domain method together with the Harmonoise/Imagine road traffic source mode was used to numerically evaluate road traffic noise reduction due to the effects of rooftop gardens. It was found that a sufficient area of rooftop garden is required before significant effects can be observed. In addition, the acoustics performance of rooftop garden increases with increasing traffic speed of light vehicles [18].

Lastly, within the limited literature, it was mentioned that substrate, plants species and the trapped layer of air between plants and the façade surface can be used as insulation against sound by absorption, reflection and deflection. Furthermore, substrate and plants tend to block sound with lower and higher frequencies respectively [19].

3. Methodology

3.1. Insertion loss experiment in HortPark

Fig. 1 shows the installation of eight different vertical greenery systems on eight concrete walls in HortPark together with an additional empty wall as the control wall (wall 0). The insertion loss experiments are performed on 5 November 2008, 18 November and 10 December 2008.

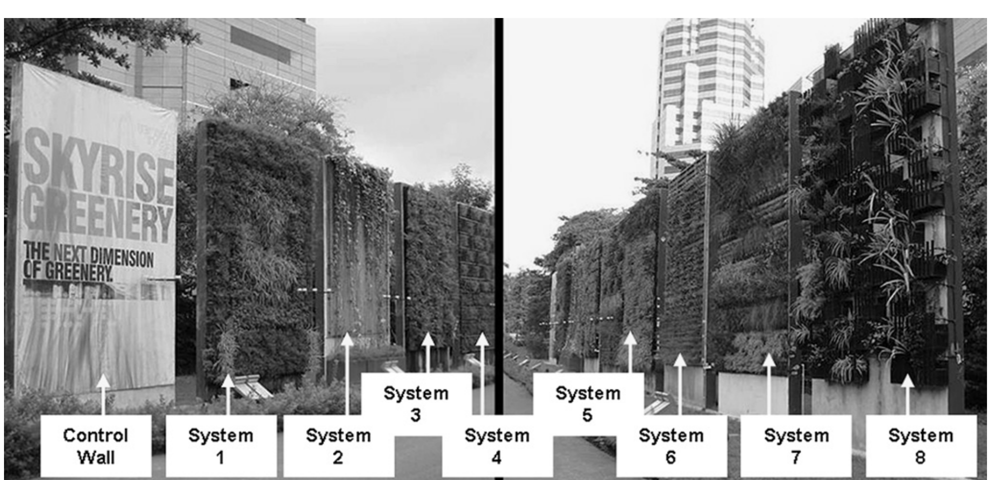

Fig. 1. Control wall and the eight vertical greenery systems in HortPark.

Table 1
Thickness of substrates and plants of vertical greenery systems in HortPark.

Vertical greenery system			Average thickness (m)		
			Substrate	Plants	Total
Green façade	Mesh system	2	0.080	0.010	0.090
	Vertical interface	1	0.250	0.100	0.350
		3	0.230	0.120	0.350
		4	0.080	0.120	0.200
Living wall	Angled interface	5	0.070	0.110	0.180
	Horizontal interface	6	0.065	0.055	0.120
		7	0.060	0.120	0.180
		8	0.280	0.200	0.480

The nine walls measure 4 m wide by 8 m high and are 0.300 m thick each. All nine walls consist of reinforced concrete frame and the interior are filled with bricks. The eight vertical greenery systems are on average 1 m above the ground although the thickness of the substrates and plants of each vertical greenery systems varies according to Table 1. The substrate of VGS 2 consists of soil inside pots that are placed on the ground while VGS 5 has an air space of 0.085 m between the wall and substrate. Lastly, Table 1 categorizes the eight vertical greenery systems into similar characteristics group for better comparison.

Insertion loss is 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 [20]. Hence, "before an object is inserted" refers to the control wall while "after an object is inserted" refers to the eight vertical greenery systems. Their difference in SPL is the insertion loss due to the addition of vertical greenery systems.

The apparatus for the acoustics experiment in HortPark consisted of the Bruel and Kjaer 4165 microphone calibrated by the Norsonic 1251 sound calibrator, Bruel and Kjaer 4224 sound speaker and the Nor-840 acoustics analyzer. Pink noise is used as the noise source and is generated for a period of 1 min. The readings are recorded within a frequency range of 63–10 kHz at one-third octave bands. The Kestrel 4500 Pocket Weather Tracker is used to determine the air temperature, relative humidity as well as the wind speed and direction. Readings show that weather conditions are not significantly different and hence unlikely to affect the experiments.

The setup of the acoustics experiment is shown in Fig. 2. The sound source is placed 2 m in front of vertical greenery systems, along the center line of the wall and directly on the ground to imitate traffic noise. Background noise is recorded in front and behind the various vertical greenery systems throughout the 3 days and found to be relatively stable.

The microphones are placed 1.5 m above the ground on tripods as that is the ear position of an average person. There are a total of four microphone positions and three readings at each microphone positions are taken and averaged. One microphone is 1 m in front of the vertical greenery systems to ensure that the noise source provides relatively stable noise level throughout the experiment. The remaining three microphones are positioned 2 m behind from the walls and 1 m away from each other. Among these three microphones, readings from the microphone positioned at the center are averaged and used for analysis while the readings from the left and right microphones are compared to ensure that there is no directional bias.

3.2. Sound absorption coefficient in the reverberation chamber of NUS

The vertical greenery system inside the reverberation chamber is constructed to determine its acoustics properties between 5 January 2009 and 7 January 2009. As shown in Fig. 3, the wooden frame has a width of 1.8 m and height of 2.8 m, having 10 racks slanting inwards at an angle of 30°. Two wooden frames are used, given a total area of 10.08 m^2. In addition, the exterior surfaces of the wooden frames are covered by aluminum foil.

The plant used is *Nephrolepis exaltata* (Boston fern), commonly found in Singapore with a high leaf area index (LAI) of 6.76. Each plant is housed in a pot with a diameter of 0.2 m and height of 0.14 m. The entire plant is about 0.2 m in height with an estimated crown diameter of 0.32 m, giving a corresponding shaded area of 0.0804 m^2.

When seven pots of plants are placed on each rack, the plants totally filled the wooden frame. Hence, 140 pots of plants are defined as covering 100% of the wall with plants. Correspondingly, 100 pots and 60 pots are defined as covering 71% and 43% of the wall, respectively. The setup of the vertical greenery system is shown in Fig. 4.

The microphones, calibrator, sound analyzer and weather tracker used are the same as the acoustics experiment in HortPark. Pink noise between frequencies 50 Hz and 50 kHz at one-third octave frequencies is used as the noise source originating from the Cesva FP120 sound source.

Two sound sources positions (sources 1 and 2) are determined; each with three different microphones positions (positions A, B and C) correspondingly. The microphones are placed 1.5 m above the ground while the speaker stands 1.4 m tall after mounting on the tripod. An excitation time of 30 s–3 min is given manually in order

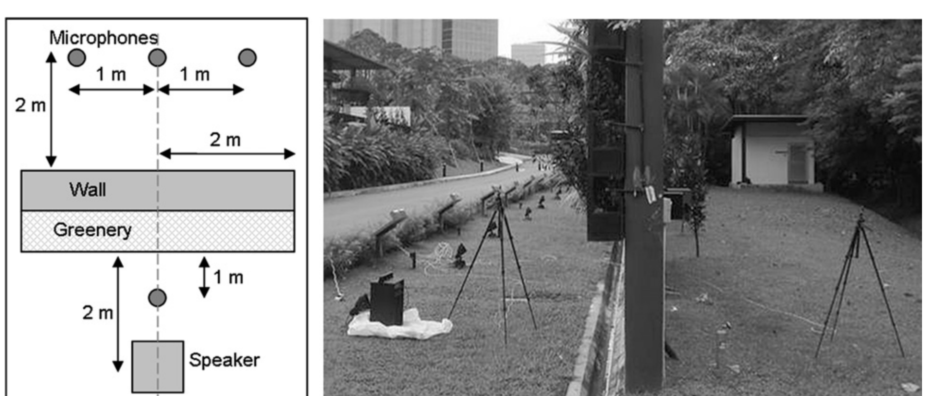

Fig. 2. Acoustics experiment setup in HortPark.

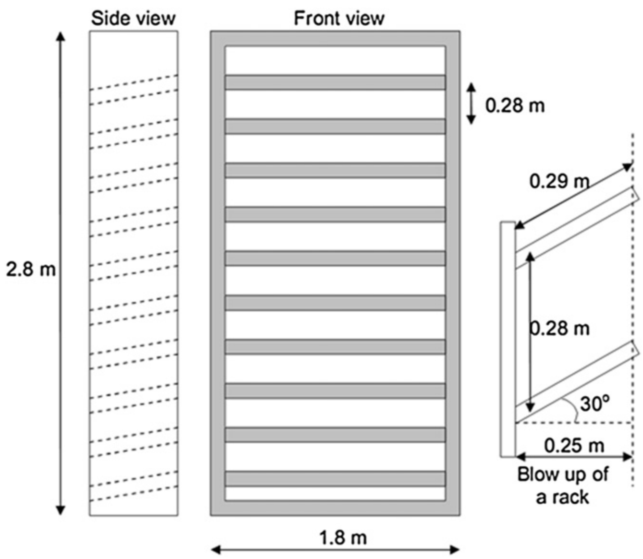

Fig. 3. Dimensions of vertical greenery system inside reverberation chamber.

to stabilize the noise. Each of the six configurations is repeated twice, giving a total of 12 measurements. The distances between the microphones, wall surfaces, vertical greenery systems and sound sources are given in Fig. 5.

The experiment was carried out according to the British Standard Method BS EN ISO 354:2003 [21]. However, there were three instances where the requirements were not met. Firstly, the volume of the reverberation chamber, V is 136 m^3, which is less than the required 150 m^3. Secondly, the values of the equivalent sound absorption area for the empty reverberation chamber against frequency does not give a very smooth curve although the values obtained are below the maximum requirement as well as within the 15% upper and lower bound. Lastly, the 24 measured relative humidity readings are within the required range except for one which is outside by 1.2%. However, these three differences are considered to be negligible.

Reverberation time, T is defined as the time required for the SPL inside the reverberation chamber to decrease by 60 dB (extrapolated) after stopping the sound source. The equivalent sound absorption area of the test specimen is defined as the difference between the equivalent sound absorption area of the reverberation chamber with and without the test specimen [21].

Although aluminum foil used to cover the exposed exterior surfaces of the wooden frame, it is observed that the interior of the wooden frame is significantly exposed when the greenery coverage is 43%. When the greenery coverage is 71%, the exposure is minimal and when the greenery coverage is 100%, the wooden frame is hardly noticeable. In order to overcome the influences of the wooden frame which is minimal as sound is mainly absorbed by leaves [9], the "reverberation chamber without the test specimen" refers to the reverberation chamber and the empty wooden frame while the "reverberation chamber with test specimen" refers to the reverberation chamber and the wooden frame together with the vertical greenery system.

Lastly, the sound absorption coefficient is defined as the equivalent sound absorption area of the test specimen divided by the area of the test specimen, S according to Eq. (1) [21]. T_2 and T_1 are the reverberation time of the reverberation chamber with and without the test specimen while c_2, c_1 and m_2, m_1 are their corresponding speed of sound and power attenuation coefficient, respectively. Since the temperature and relative humidity readings within the reverberation chamber are similar with and without the test specimen, the speed of sound (determined to be 346 m/s) and power attenuation coefficient are assumed to be constant throughout the experiment and the calculation of the sound absorption coefficient simplified to Eq. (2).

4. Discussion and analysis

4.1. Insertion loss

Readings from the microphone in front of the wall are found to be stable. Hence, the observed insertion loss is not caused by differences in noise source level. Furthermore, the SPL readings at the left and right positions behind the wall are found to have similar readings, verifying that there is no directional bias. Lastly, all of the readings obtained for analysis are 10 dB above the background noise. Therefore, the 3 SPL readings from the central position behind the wall are averaged and used for analysis. The average SPL readings is separated into four zones, zone A from 63 Hz to 125 Hz, zone B from 125 Hz to 1250 Hz, zone C from 1250 Hz to 4 kHz and zone D from 4 kHz to 10 kHz as each zone has different characteristics.

Diffraction is a concern because it significantly affects the SPL for low frequencies. However, with a wall width of 4 m and assuming 350 m/s as the speed of sound, only frequencies of 87.5 Hz and below will have wavelength greater than the wall width. This frequency range falls within zone A and hence zones B, C and D are unlikely to be affected. Furthermore, if diffraction is present, it will

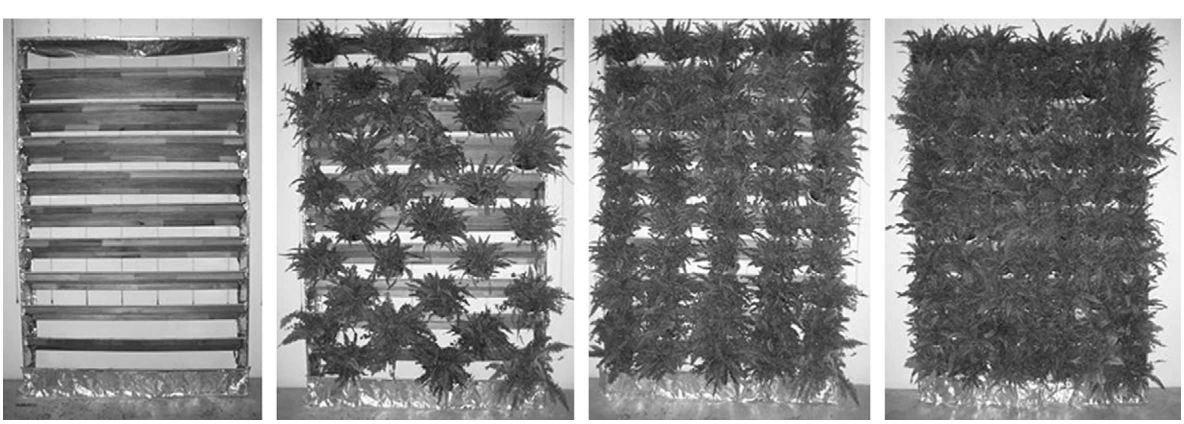

Fig. 4. Vertical greenery system with empty, 43%, 71% and 100% greenery coverage densities in reverberation chamber (from left to right).

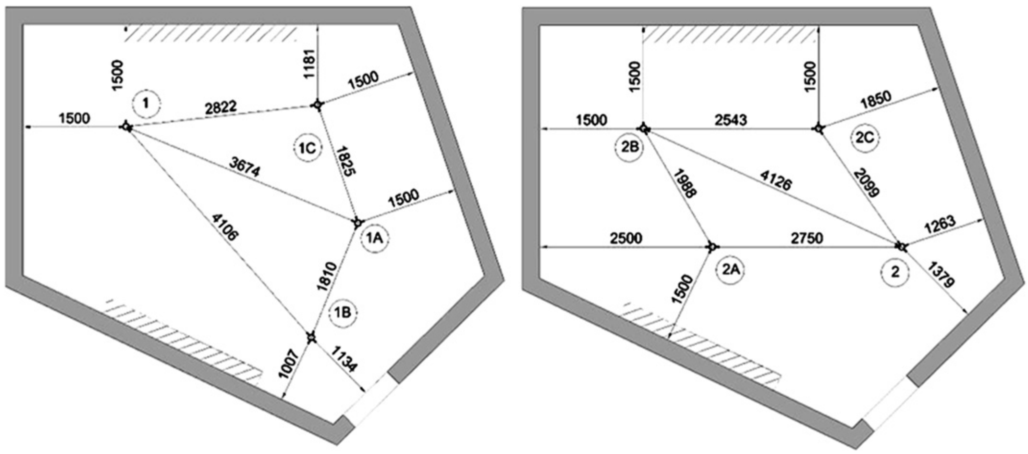

Fig. 5. Positions of vertical greenery system (shaded regions), sound source 1 (left) and 2 (right) with their corresponding microphones (A, B, C) inside the reverberation chamber (in mm, all dimensions to the wall are at right angles).

be encountered by the entire eight vertical greenery systems and the control wall. Therefore, diffraction will not pose an issue as insertion loss is a relative difference in SPL.

The average SPL readings and insertion loss for each vertical greenery systems are shown in Fig. 6 and 7, respectively while their plants and arrangements are given in Fig. 8. In addition, their highest and lowest values are summarized in Table 2.

VGS 1 shows a highest insertion loss of 5.6 dB in zone B which is close to the perception of "clearly noticeable". The substrate is soil sparsely held in small planter cages and versicell planters located at the bottom of the wall have a thicker layer of substrate, which probably results in the higher insertion loss.

The density and coverage of both greenery and substrate are the lowest for VGS 2. However, its highest insertion loss in zone B is

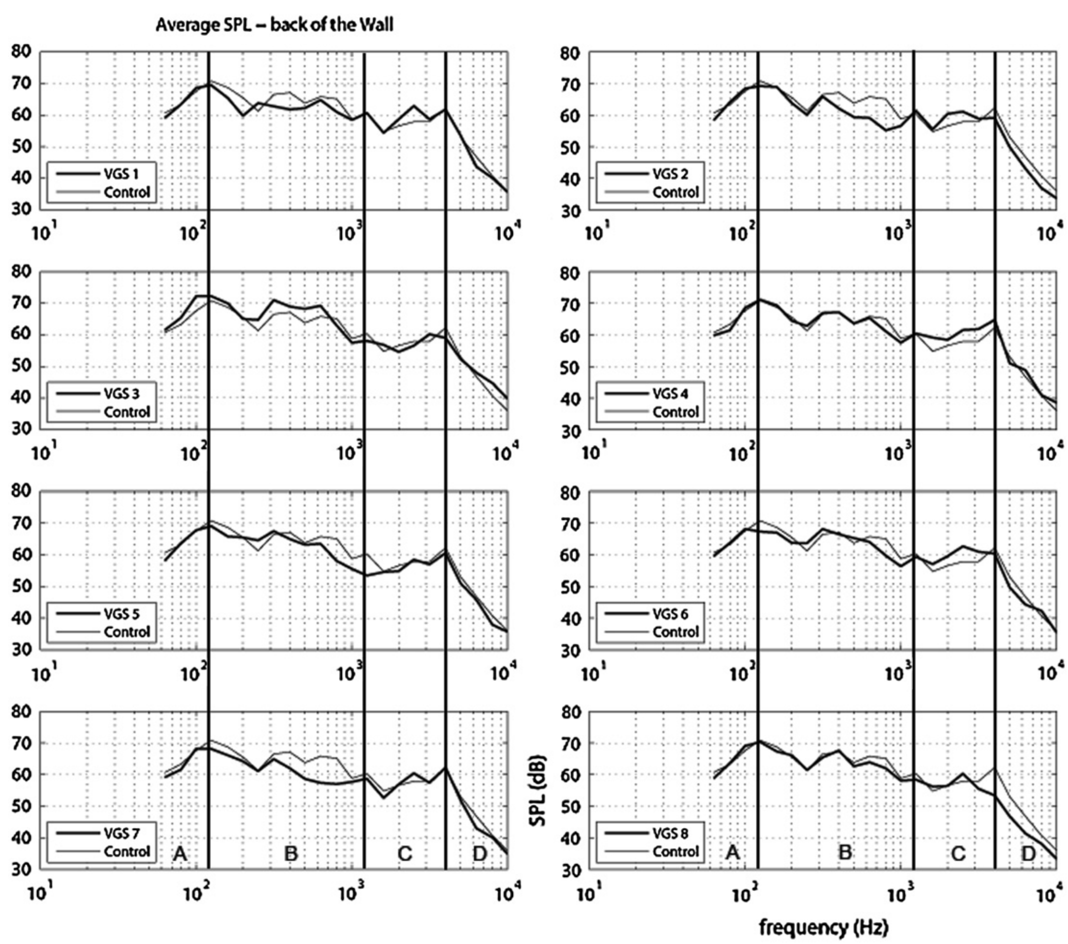

Fig. 6. Average SPL readings at the back of the entire eight vertical greenery systems during the acoustics experiments in HortPark.

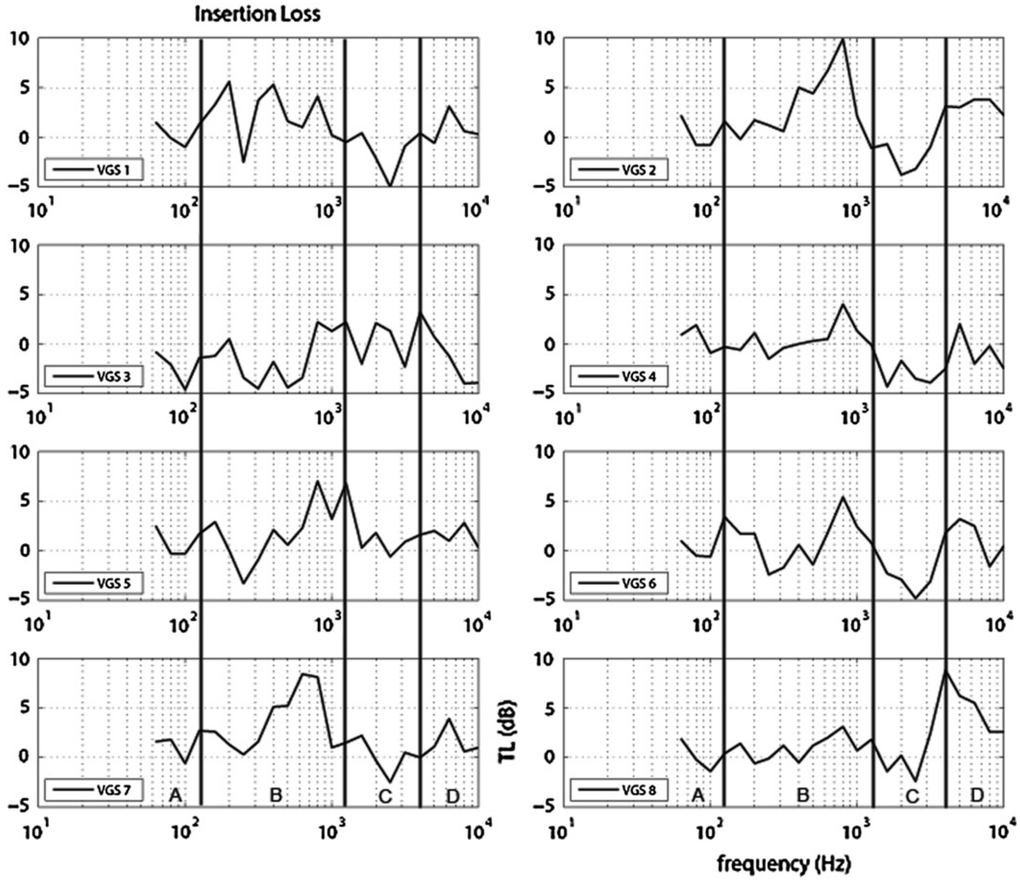

Fig. 7. Average insertion loss for the entire eight vertical greenery systems during the acoustics experiments in HortPark.

a high value of 9.9 dB corresponding to the 800 Hz one-third octave band. This can be due to the substrate, which is soil in planter pots 0.610 m thick and placed at the same ground level as the sound source. Therefore, a significant amount of sound is absorbed, contributing to the high insertion loss. Zone D shows a maximum insertion loss of 3.8 dB which is "perceptible" to human hearing. As the greenery of VGS 2 is very sparse, the plants used may have fairly good acoustical absorptive properties.

Greenery in VGS 3 is distributed sparsely with a few areas with considerable plants thickness. Furthermore, there is a high exposure of substrate without any plant coverage. The substrate is soil of thickness 0.230 m which is relatively thicker compared with the rest of the other vertical greenery systems. However, VGS 3 exhibited a strange insertion loss reading where most of the values are negative across all four zones, reaching a minimum value of −4.5 dB in zone B. The presence of the substrate without any greenery may be a possible reason for negative insertion loss although the principle behind it is unclear.

VGS 4 has mostly plants with small leaves and is distributed evenly throughout the surface. The thickness and density of the plants are also moderate. However, there are gaps of considerable width between the modular panels which are supported by stainless steel casing. Hence, VGS 4 exhibits almost zero insertion loss and a low maximum of 4.0 dB within the 800 Hz one-third octave band in zone B. These gaps may be the regions where noise is transmitted directly through the wall.

VGS 5 has regions of empty gaps without any substrate or greenery. Moreover, there is an air space of 0.085 m thick between the wall and VGS 5. This air gap acts a cushion that further isolate the sound energy after it is transmitted through. Therefore, the highest insertion loss in zone B is 7.0 dB while in zone D a maximum insertion loss of 2.8 dB is obtained.

The plants of VGS 6 have small leaves and covered the wall in high density. However, there is a distinct arrangement where the plants and substrate within the mini pots hardly overlap with one another, forming alternate rows of greenery and substrate. The highest insertion loss in both zones B and D are 5.4 dB and 3.2 dB, respectively as shown in Fig. 9. The relatively lower insertion loss in zone B may be explained by the thickness of the substrate which is only 0.065 m thick. On the other hand, the low insertion loss in zone D may suggest that plants alone is not very effective in absorbing or scattering noise.

VGS 7 consists of pockets of substrate filled with plants. The greenery is very dense and covered the entire wall. In zone B, a maximum insertion loss of 8.4 dB is registered at the 630 Hz one-third octave band. As the substrate does not cover the entire wall, this arrangement of the greenery and substrate may have provided a good combination in noise reduction. Due to the lack of thick leaves, the noise reduction properties of these plants are not very good, resulting in zone D having a highest insertion loss of 3.9 dB.

In VGS 8, the substrate and greenery have a thickness of 0.280 m and 0.200 m, respectively. However, the plants are not evenly distributed around the wall, exposing a large wall surface directly to the sound. Therefore, in zone B a low maximum insertion loss of 3.1 dB is observed. However, the highest insertion loss of 8.8 dB is obtained at the 4 kHz one-third octave frequency band in zone D. This may be due to the nature of vertical greenery system 8 and require further investigation.

Fig. 8. Vertical greenery systems 1–8 (left to right, top to bottom) in HortPark.

4.2. Overall trends

There have been many claims that rooftop gardens can reduce sound by as much as 40 dB. It is published that a rooftop garden with 12 cm and 20 cm of substrate can reduced sound by 40 dB and 50 dB, respectively [19,22]. However, there are little scientific evidences that back these claims [19].

In zone A, the frequencies between 63 Hz and 125 Hz, insertion loss analysis is not performed. This is because throughout the entire eight vertical greenery systems, the insertion loss is close to zero. It is due to the diffraction in low frequencies where the sound wave bends around an obstacle. Furthermore, the SPL readings are not higher than the background noise by 10 dB and hence, not suitable for analysis.

Zone B covers the frequency spectrum between 125 Hz and 1250 Hz. As frequencies increase, insertion loss generally shows an increasing trend which peak around 800 Hz with varying magnitude before decreasing. Furthermore, from Fig. 6, the patterns of the SPL readings of the entire eight vertical greenery system are very

Table 2
Summary of insertion loss.

Vertical greenery system	Insertion loss (dB)			
	Zone B: 125–1250 Hz		Zone D: 4–10 kHz	
	Lowest	Highest	Lowest	Highest
2	−1.1	9.9	2.2	3.8
1	−2.5	5.6	−0.6	3.1
3	−4.5	2.2	−4.0	3.2
4	−1.5	4.0	−2.5	2.0
5	−3.3	7.0	0.3	2.8
6	−2.4	5.4	−1.6	3.2
7	0.3	8.4	0.0	3.9
8	−0.6	3.1	2.6	8.8

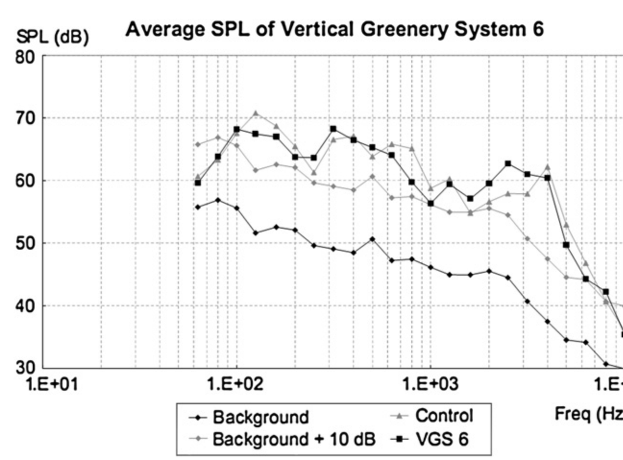

Fig. 9. Average SPL readings at the back of VGS 6 during the acoustics experiments in HortPark.

different from that of the control wall, implying that the presence of substrate changes the acoustics properties.

Zone C, ranging from 1250 Hz to 4 kHz, consists of mostly negative insertion loss. The possible explanation is the focusing effect of vertical greenery systems. Due to the periodic arrangement of greenery, reflections and scatterings may focus sound energy onto certain region near the surfaces. As a result, the SPL readings just in front of the wall at these regions may be higher than the control wall's reading. This will lead to corresponding higher SPL readings at the back of the wall and a negative insertion loss.

Lastly, zone D from 4 kHz to 10 kHz has mostly positive insertion loss with peaks at various different frequencies. At 10 kHz one-third octave band, the SPL readings are only 8–9 dB higher than the background, similar to that shown in Fig. 9. However, this does not affect the analysis of zone D. From Fig. 6, the pattern of the SPL readings of the entire eight vertical greenery system is very similar to the control wall, implying that the acoustics properties of the wall remain unchanged. The insertion loss is due to a reduction in sound magnitude from scattering by greenery before it is transmitted.

4.3. Sound absorption coefficient

As shown in Fig. 10, the reverberation time with an inclusion of vertical greenery system reduces tremendously, especially within the frequency range of 200 Hz to 1 kHz. The reduction in reverberation time is smaller from 1 kHz to 5 kHz. This observation is in line with the insertion loss experiment in HortPark. The substrate, which is soil, performs well in low frequencies by absorbing the acoustics energy, resulting in a large drop in reverberation time. On the other hand, plants perform better in high frequencies. However, their mechanism is to scatter the sound noise. Hence, the reduction in reverberation time is not significant.

Moreover, the reduction of reverberation time is relative to the greenery coverage. The reverberation time increases when the greenery coverage (and number of pots of plants) decreases.

The average sound absorption coefficients of the vertical greenery system for the three greenery coverage densities are calculated and plotted on Fig. 11. As frequency increases, the differences between sound absorption coefficients for 100%, 71% and 43% greenery coverage increase. For low frequencies between 100 Hz to 250 Hz, the differences in sound absorption coefficients among different greenery coverage are small. As the frequency ranges increase, the differences widen. After 1 kHz, the differences in sound absorption coefficients are fairly constant.

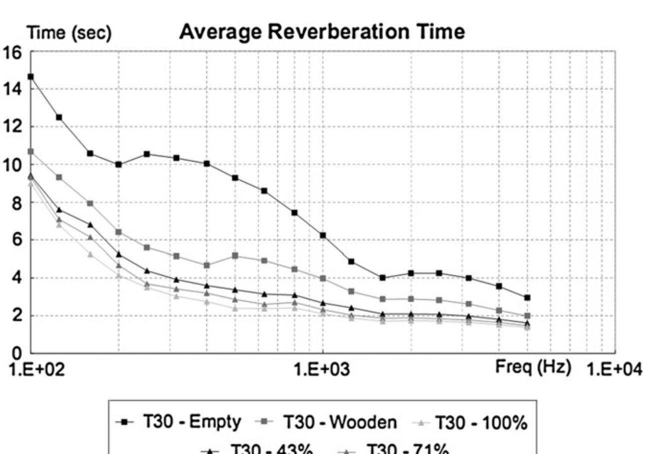

Fig. 10. Average reverberation times (T30).

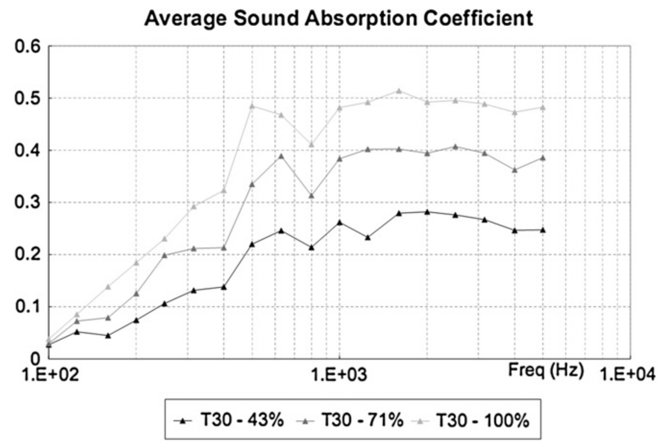

Fig. 11. Average sound absorption coefficients.

The sudden drop in sound absorption coefficients at 800 Hz frequency is due to the relatively steeper gradient of the reverberation time of the reverberation chamber without the test specimen compared to that with the test specimen. This explains why the dip is experienced in all three different greenery coverage densities. This dip is commonly experienced in many reverberation chamber experiments and may be due to the resonance characteristics of the vertical greenery systems.

Fig. 12 plots the sound absorption coefficients of commonly used building materials in Singapore together with the vertical greenery system [23]. Most of the materials such as brick, concrete and glass exhibit low sound absorption coefficients, which remain constant or decrease with increasing frequencies. Coarse concrete block is comparable with vertical greenery system at 71% greenery coverage and outperforms all vertical greenery systems at low frequencies regardless of greenery coverage. The sound absorption coefficient of carpet on concrete is comparable at high frequencies but performed poorly at low frequencies.

Therefore, the potential of vertical greenery system is clearly shown. However, the plant used in the reverberation chamber,

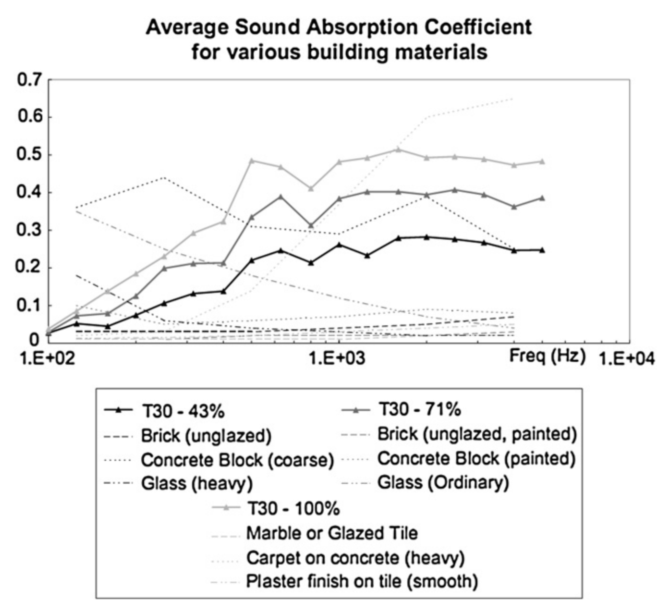

Fig. 12. Sound absorption coefficients of vertical greenery system and other building materials.

Table 3
Summary of sound absorption coefficient.

Frequency (Hz)	Sound absorption coefficient (greenery coverage)		
	43%	71%	100%
100	0.06	0.04	0.04
125	0.12	0.10	0.09
160	0.10	0.11	0.14
200	0.17	0.18	0.18
250	0.25	0.28	0.23
315	0.31	0.30	0.29
400	0.32	0.30	0.32
500	0.51	0.47	0.49
630	0.57	0.55	0.47
800	0.50	0.44	0.41
1000	0.61	0.54	0.48
1250	0.54	0.57	0.49
1600	0.65	0.57	0.51
2000	0.66	0.56	0.49
2500	0.64	0.57	0.50
3150	0.62	0.56	0.49
4000	0.57	0.51	0.47
5000	0.58	0.54	0.48

Nephrolepis exaltata, has a high LAI value of 6.76. Hence, this result reflects the maximum and not the medium performance of vertical greenery system.

5. Conclusion

5.1. Insertion loss

The insertion loss experiment shows stronger attenuation at low to middle frequencies due to the absorbing effect of substrate while a smaller attenuation is observed at high frequency spectrum due to scattering from greenery. Hence, the 8 vertical greenery systems in HortPark are more effective at reducing lower frequency noise source. Generally, VGS 2, 7 and 8 exhibit better insertion loss properties.

However not all vertical greenery systems exhibit a good noise reduction. From Table 2, VGS 2, 7, 5, 1 and 6 have a reduction of around 5–10 dB for low to middle frequency range (zone B). This acoustics reduction is perceptible or even clearly noticeable for human perception in the change of sound intensity. In the high frequencies (zone D), VGS 8 clearly outperforms the rest with a highest insertion loss of 8.8 dB. The rest of the vertical greenery systems have an insertion loss ranging from 2 dB to 3.9 dB.

However, due to the high cost of installation and maintenance, vertical greenery systems should not be chosen only for acoustics consideration. There are other wall facades like plastering and gypsum board which are more economic. Lastly, to obtain a reasonable insertion loss, care must be taken to ensure that there are no empty gaps within the vertical greenery system which allow transmission of noise without significant absorption or scattering.

5.2. Sound absorption coefficient

The sound absorption coefficient of the vertical greenery system in the reverberation chamber has one of the highest values compared with other buildings materials and furnishings. As shown in Table 3, the sound absorption coefficient increases with increasing frequencies.

Furthermore, the relationship between the greenery coverage and the sound absorption coefficient is observed that with greater greenery coverage, there is an increase in the sound absorption coefficient. Therefore, vertical greenery systems may also be useful if they are installed internally to enhance speech privacy despite the high cost.

5.3. Recommendations

Results highlight that the acoustics benefits of vertical greenery systems in the tropical environment are promising. To further advance the research, acoustics studies of vertical greenery systems should be performed on actual building facades in an attempt to reveal more acoustics insight. Furthermore, when the vertical greenery systems are installed on actual building facades, results can be simulated and compared for a better understanding of the principles behind the effects of vertical greenery systems on sound insulation.

Many factors such as the structure, materials and dimensions of the panels, the type, composition, depth and moisture content of the substrate as well as the various plants species have an impact on the acoustic performance of vertical greenery systems. There is a need to analyze these factors individually to determine their influence on the other factors and overall acoustics performance of vertical greenery systems.

In all, with all the encouraging acoustics results towards vertical greenery, it is with anticipation that more research will lead to a rapid development and implementation of vertical greenery systems in the built environment.

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Appendix. Equations

Equivalent sound absorption coefficient of test specimen:

$$\alpha_s = \frac{A_T}{S} = \frac{V}{S}\left[55.3\left(\frac{1}{c_2T_2} - \frac{1}{c_1T_1}\right) - 4(m_2 - m_1)\right] \quad (1)$$

Equivalent sound absorption coefficient of test specimen (simplified):

$$\alpha_s = \frac{55.3V}{cS}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \quad (2)$$

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