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Ensuring the Safety of Buildings by Reducing the Noise Impact through the Use of Green Wall Systems

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Abstract: Modern environmental problems are caused by increased energy consumption and the urban heat island effect. Urban noise pollution is another big problem in the Megacities. Ensuring safety with reducing hazards in the urban space is one of the priority tasks of the urban city centers. One solution is the use of green technologies in the construction of office and residential real estate. In this research, we provide the analysis of reducing the noise impact through the use of different green wall systems, such as modular, hydroponic and container, analyzing their benefits and disadvantages in terms of operation and maintenance. After that, we chose hydroponic systems as the most efficient ones and examined different conditions of the system and how these types reduce the noise analyzing absorption coefficient. As a result, we found out that the efficiency of the hydroponic green wall system depends on the humidity of the substrate and the presence of the plants, which confirms the importance of vegetation in reducing noise impact in urban environment.

Keywords: green wall system; living wall system; noise impact; vertical greening systems; green building; urban environment

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Citation: Shushunova, N.; Korol, E.; Luzay, E.; Shafieva, D.; Bevilacqua, P. Ensuring the Safety of Buildings by Reducing the Noise Impact through the Use of Green Wall Systems. *Energies* **2022**, *15*, 8097. https://doi.org/10.3390/en15218097

Academic Editors: Ayman S. Mosallam, Haohui Xin, Brahim Elbhiri, Shaohua He and Shadi M. Saadeh

Received: 16 September 2022
Accepted: 22 October 2022
Published: 31 October 2022

1. Introduction

In the modern world, the problem of preserving the ecologically favorable environment is rising abruptly due to the accelerated growth of the urbanization: the lack of green spaces in large cities, global warming, increased noise pollution, deteriorating air quality, extensive consumption of electricity and water are the consequences of mindless mass development of territories. These above-mentioned aspects negatively affect people, worsening their physical and psychological health [1–3]. For example, according to the results of a WHO study, excessive noise exposure impairs hearing, develops cardiovascular diseases, and reduces human productivity and even the standard of living by 10–12 years; dirty air provokes the development of lung cancer and acute respiratory diseases [4,5]. One of the most effective and aesthetic ways for modern cities to improve the microclimate is the introduction of green architecture. In a large number of countries around the world, buildings with vertical green are beginning to be erected, including apartment buildings, hotels, and offices and government buildings, decorated with a wide variety of plants [6].

The human body is a complex ecosystem and requires three basic things to live a full life: food, water and oxygen. Oxygen is the most important factor in human existence. However, the rapid development of society and civilization leads to a reduction in oxygen in the atmosphere. This is especially true in large metropolitan areas, where a huge number of production machines are concentrated, which are the main producers of carbon dioxide and absorbers of oxygen. It is in megacities that there is a constant lack of oxygen [7]. In this regard, a very important task is the development of green spaces in urban areas. However, this, unfortunately, is associated with certain difficulties, namely, the lack of sufficient space for laying out parks and green areas [8,9]. Therefore, the development of vertical gardening of cities today is one of the priority areas for the development of urban infrastructure, which is given great attention all over the world [10–14].

Due to the identified problem, one of the tasks of modern design is the construction of buildings and structures using technologies that help protect the environment and reduce the negative impact on people [15]. There are many systems of international standards and criteria are being developed to assess the environmental friendliness of buildings, such as LEED (USA), BREEAM (UK), DGNB (Germany), etc. These rating systems are a set of quantitative and qualitative indicators characterizing the level of comfort, energy efficiency and environmental friendliness of buildings. Following the principles of sustainable construction, which are described in these standards, will lead to economic benefits and reduced energy consumption.

For example, a LEED Gold certified US Treasury building saves more than USD 1 million of US taxpayers a year through smart and integrated strategies to reduce energy and water consumption. Use of greening systems on the territory and buildings is one of the methods of green construction, which allows to use a small space for good purposes effectively. Greening of walls does not incur large construction costs, is available in most parts of the world, is easy to operate and, most importantly, is very effective [16]. Green roofs also perform as modern and effective solution of reducing heat from buildings. The study in Japan [17] found heat reductions, which were about 50% per year, and work in Ottawa [18] found a 95% heat reduction per year by using green technologies. Green roofs can also reduce the cooling load on multistory residential building by 6–10 % during the summertime [19,20].

In these environmentally friendly systems, plants act as natural biofilters, because they have the ability to change the chemical composition and ionize air molecules, as well as absorb and reflect sound waves [21] and increase air moisture [22]. Many scientists have conducted research on green technologies and their impact on both outdoor and indoor microclimate [23–28]. The installation of green roof and living wall systems on the existing buildings is a way to improve the quality of the urban environment. Technological benefits of green systems are connected with reduction in the airborne noise and energy cost savings by 40% [29–35]. Some benefits of green modular construction for high-rise buildings were studied [36–40]. This study examines the rational technological characteristics of green wall systems based on test methods, research of their calculated absorption parameters.

Thus, green spaces help to improve the microclimate of premises, increase sound insulation and air quality, and solve the problem of lack of green living areas. Moreover, vertical landscaping is a way to diversify and improve the architectural appearance of buildings. Landscaping systems are successfully used in many countries of the world, for example, One Central Park (Sydney, Australia), Bosco Verticale (Milan, Italy), Robinson Tower (Singapore), Parkroyal Collection Pickering (Singapore). There is a lot of research on the use of plants in construction. The purpose of this work is to compare different vertical gardening technologies to identify the most convenient system to operate and design, as well as the most noise-insulating coating for using it in in industrial premises.

To achieve this goal, the following tasks were carried out:

- Consider different landscaping systems;
- Identify the pros and cons of each of them according to certain criteria;
- Evaluate the noise-absorbing characteristics;
- Determine the most soundproofing system.

2. Materials and Methods

In this study the methods of comparative analysis of the various options for vertical greening systems were applied. Based on the results of comparison of these systems, the choice of the best option was made according to the following parameters: installation availability, ease of use and reduction in noise impact. This study also provides a detailed description of the structure of green wall systems.

Depending on the system, the main components of green walls can be: plants, substrate, supporting elements around which plants grow, and a system of pipes and pumps that delivers water and fertilizer. According to the principle of operation, modern wall landscaping systems are: felt—hydroponic systems; modular—using a substrate and container technology—planting in pots (Figure 1).

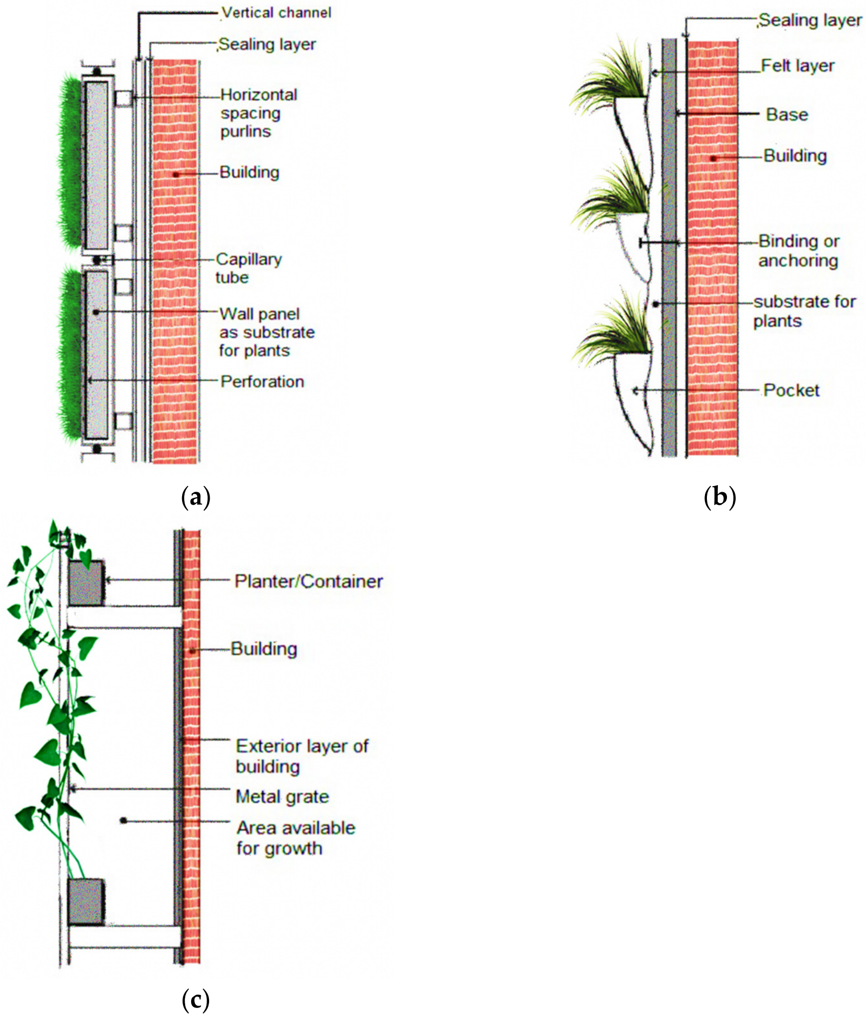
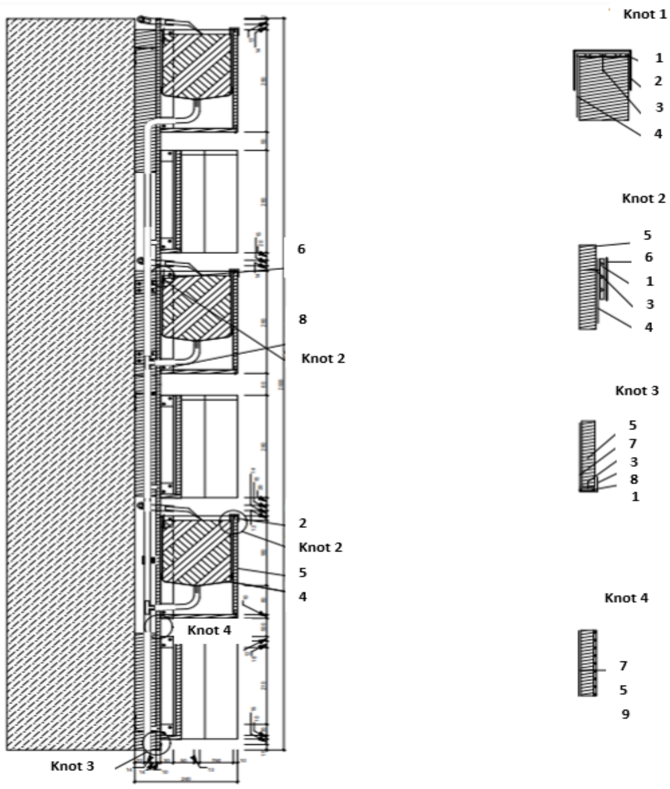


Figure 1. Variants of Existing vertical greening systems: (**a**) felt—hydroponic systems; (**b**) modular—using a substrate; (**c**) container technology—planting in pots.

For a comparative analysis, it is necessary to consider in detail all types of vertical greening systems (Figure 1).

Hydroponic green wall systems consist of modular containers or large panels, materials of containers can act as a water retentive sponge. The advantage of this system is that there is no structural decay of the growing medium [41].

An innovative green wall system, designed and patented by the authors is shown on the Figure 2. These green wall systems can be made from plastic—HDPE or glass plastic. The inclined version of such covering systems has the greatest aesthetic expressiveness, as well as a number of advantages from a constructive point of view (Figure 2b).



(**a**)

(**b**)

Figure 2. Vertical greening systems, designed and patented by the authors: (**a**) Section view of innovative modular green wall systems; 1—sealant, 2—profile, 3—constructive bracket, 4—geotextile bag, 5—wooden plate, 6—plastic strip, 7—vapor barrier, 8—plastic corner, 9—water-based paint; (**b**) 3D view.

We decided to develop the most convenient system to operate and design or the most-insulating coating for use on industrial premises, which is shown on the Figure 2.

Modular green wall systems are easy and quick to assemble; moreover, they are convenient to replace in case of breakage or seasonal dismantling. This type of green wall system allows to diversify the types of vegetation, not limited to vertical climbing plant species [42,43].

The basis of the structure in the container green systems is the supporting waterproof metal frame, which is divided into three types: frame grid, built-in frame rack, portable frame rack with guides. An irrigation system is fixed directly on the frame itself. This system is a huge network of hollow pipes, and pots with soil substrate, in which the plants are subsequently planted. For each pot, a personal irrigation tube is placed to supply water and fertilizer (Figure 2).

The comparative analysis of different types of green wall systems were shown in the Table 1.

Table 1. The comparative characteristics of different types of green wall systems.

Parameter	Hydroponic System	Modular System	Container System
Rooting Space	Brackets protruding from the load-bearing wall	Substrate-holding containers	Supporting waterproof metal frame: frame grid, built-in frame rack, portable frame rack with guides
Substrate	Horticultural foam, mineral fibre, felt mat	Soil substrate in water permeable, synthetic fibre bag	Soil substrate
Maintenance	Pruning/replacement	Pruning/replacement	Pruning/replacement
Advantages	No structural decay of the growing medium	The growing medium support the plant and facilitates water, providing nutrient access	Irrigation system is connected to the water supply and sewerage system
Disadvantages	Constant management and maintenance	Accumulation of salts in the growning medium, high system weight	

The research focused mostly on the hydroponic green wall systems. We chose this type because of the lack of soil in it. In the modern world, it is more convenient to use a substrate in the form of a foam sponge or mineral fiber. Moreover, it includes an automatic irrigation and fertilizer supply system, which greatly facilitates the maintenance of this technology.

To identify the most noise-absorbing hydroponic system, we have made a request to manufacturing companies to provide us with data, how exactly their greening systems reduce the noise level. The requested information for this article were: tables with measurements of noise attenuation, graphs of changes in the noise-absorbing capacity of systems consequent to alterations in the characteristics of the substrate, equations for gauging the absorption coefficient.

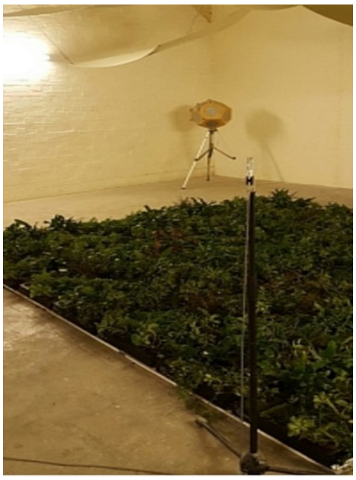
About 14 companies from all over the world were interviewed (Biotecture (UK), Natural Greenwalls (UK), Meamea (France), Green Urban Life GmbH (Austria), Greenmood HQ (Belgium), Moos manufaktur (Germany), Urbanscape (Germany), ANS Global (UK), Live Wall (USA), Sempergreen (Netherlands), McCaren Designs (USA), Greenarea (Spain), LinfaDecor (Italy) and Sundar (Italy).

The measurements of sound absorption were made in the AIRO Acoustics Laboratory (UKAS accredited testing laboratory No. 0483), considering three configurations of Biotecture Living Wall System. Measurements of Sound Absorption Coefficient (α_s) were conducted in accordance with British Standard BS EN ISO 354 [42], Weighted Sound Absorption Coefficient (α_w) and Sound Absorption Class, are derived from these measurements in accordance with British Standard BS EN ISO 11654 [43]. The specimen comprised the Biotecture Living Wall System, which was installed for test directly over the floor of the reverberation chamber to cover an area of 3.00 m × 3.60 m thereby satisfying the area and aspect ratio requirements of BS EN ISO 354 (Figure 3).

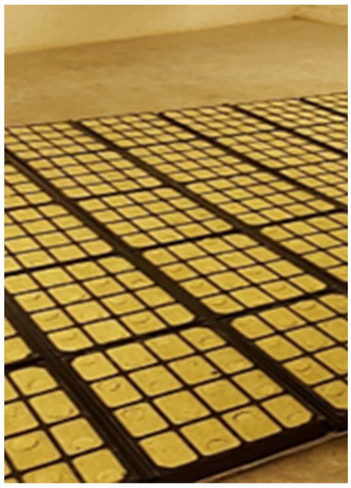
Chamber Conditions	Volume	Air Temperature	Relative Humidity	Air Pressure
Empty Chamber	221 m³	8 °C	85%	1008 mbar
Chamber with Specimen	221 m³	8 °C	85%	1008 mbar

Figure 3. Conditions for conducting experiments.

The system included a 15 mm thick Palight Board (550 to 700 kg/m^3) which was used as a waterproof backing and mounting board. This was overlaid by a geotextile drainage layer, with aluminium fixing rails, driplines and cover strips at 450 mm centres. 40 Biotile Panels with 600 × 450 mm modular dimensions were clipped into the fixing rails in a 5 panel long × 8 panel high array. Each Biotile Panel consisted of a 3 mm plastic framework with a 55 mm thick Grodan growing medium of 75 kg/m^3 Rockwool mineral wool. The front face of each Biotile Panel was sub-divided into 16 cells by the plastic framework with each cell including a pre-cut 50 mm diameter removable plant plug (Figure 4).



(a)



(b)

Figure 4. Biotecture green wall wall system: (**a**) Living wall system, with plants; (**b**) green wall system, without plants.

1. Biotecture green wall system with fully planted panels (test no. L/3360/1)

The panels were wet with an average moisture content of 60 to 70%, and were fully planted with 640 plants of a mixed perennial plant selection.

2. Biotecture green wall system with dry panels (test no. l/3360/2)

The panels were dry, did not include plants but did include the removable Grodan growing medium plugs.

3. Biotecture green wall system with wet un-planted panels (test no. l/3360/3)

The panels were wet with an average moisture content of 60 to 70%, did not include plants but did include the removable Grodan growing medium plugs.

Sound absorption is measured in a diffuse field when sound is falling on the sample from all directions. The sample is placed directly above the floor to create a repercussion chamber. The chamber rests on resilient supports that provide good acoustic insulation from the outside of the building. To ensure good diffusion of the sound field, the walls are non-parallel, the ceiling is sloping and twenty randomly suspended diffuser panels with an area of 37.2 square meters. A constant sound source with a continuous spectrum in the frequency bands of interest is used to drive an omnidirectional loudspeaker located in the chamber. The chamber repercussion time is determined using the intermittent noise method with three attenuation measurements taken at each of the four microphone positions for each of the three loudspeaker positions to obtain a good average value in each of the one-third octave intervals from 100 Hz to 5000 Hz [44]. The test is carried out with the sample installed inside the chamber, and also in the absence of the sample and the associated frame.

Sound absorption coefficient (α_s) of the parameter is calculated using the formula (Figures 5 and 6):

$$\alpha_s = 55.3\,\frac{V}{S}\left(\frac{1}{c_2 T_2} - \frac{1}{c_1 T_1}\right) - 4V(m_2 - m_1) \quad (1)$$

where: V is the volume of the empty repercussion chamber (m^3);

S is the area of the test sample (m^2), in each case, it is equal to 10.8 m^2;

T_1 is the mean repercussion time of the empty repercussion chamber (seconds);

T_2 is the mean repercussion time of the repercussion chamber with the test sample installed (seconds);

m_1 and m_2 are the power attenuation coefficient at T_1 and T_2 calculated according to ISO 9613:1993 [44];

c_1 and c_2 are the velocity of sound.

$$c = 331 + 0.6t$$

where: t is the air temperature of the repercussion chamber (Celsius), in each case, it is equal to 8 °C.

In Figure 5 we show the measurements of the coefficients at different sound frequencies.

Frequency (Hz)	α_s	α_p
50	0.05	
63	0.04	0.05
80	0.05	
100	0.10	
125	0.12	0.15
160	0.23	
200	0.34	
250	0.59	0.55
315	0.75	
400	0.83	
500	0.76	0.75
630	0.69	
800	0.69	
1000	0.72	0.70
1250	0.74	
1600	0.77	
2000	0.81	0.80
2500	0.86	
3150	0.84	
4000	0.87	0.85
5000	0.86	
6300		
8000		
10000		

(**a**)

Frequency (Hz)	α_s	α_p
50	0.08	
63	0.07	0.05
80	0.05	
100	0.21	
125	0.32	0.35
160	0.55	
200	0.87	
250	1.07	1.00
315	1.16	
400	1.09	
500	1.09	1.00
630	1.13	
800	1.07	
1000	1.06	1.00
1250	1.08	
1600	1.04	
2000	1.02	1.00
2500	1.05	
3150	1.01	
4000	1.00	1.00
5000	0.96	
6300		
8000		
10000		

(**b**)

Frequency (Hz)	α_s	α_p
50	0.03	
63	0.07	0.05
80	0.04	
100	0.10	
125	0.13	0.15
160	0.21	
200	0.26	
250	0.48	0.45
315	0.66	
400	0.69	
500	0.59	0.60
630	0.50	
800	0.46	
1000	0.48	0.45
1250	0.48	
1600	0.50	
2000	0.51	0.50
2500	0.52	
3150	0.55	
4000	0.55	0.55
5000	0.57	
6300		
8000		
10000		

(**c**)

Figure 5. Measurements of sound absorption coefficient according to BS EN ISO 354:2003: (**a**) Biotecture green wall system with fully planted panels; (**b**) Biotecture living wall system with dry panels; (**c**) Biotecture green wall system with wet un-planted panels.

Frequency Hz	Empty Chamber	Mean Reverberation Times, secs		
		Chamber with Test Specimen		
		Test No. 1	Test No. 2	Test No. 3
50	7.99	7.15	6.66	7.50
63	8.81	8.04	7.38	7.45
80	7.24	6.60	6.49	6.62
100	8.52	6.84	5.60	6.76
125	6.93	5.56	4.19	5.51
160	5.61	4.07	2.93	4.17
200	5.56	3.56	2.28	3.87
250	6.05	2.94	2.07	3.26
315	6.64	2.67	2.02	2.89
400	6.95	2.57	2.14	2.86
500	6.99	2.72	2.15	3.15
630	7.04	2.88	2.10	3.44
800	7.13	2.89	2.18	3.62
1000	6.80	2.78	2.16	3.47
1250	6.42	2.66	2.10	3.36
1600	5.78	2.49	2.08	3.12
2000	5.02	2.27	1.99	2.85
2500	4.23	2.03	1.82	2.55
3150	3.39	1.84	1.68	2.18
4000	2.70	1.59	1.50	1.87
5000	2.04	1.34	1.29	1.52

Figure 6. Mean reverberation times: (Test No.1) Biotecture living wall system with fully planted panels; (Test No.2) Biotecture living wall system with dry panels; (Test No.3) Biotecture living wall system with wet un-planted panels.

Weighted sound absorption coefficient (α_w) according to [45] a single-valued frequency-independent value equal to the value of the reference curve at 500 Hz after it has been shifted.

3. Results and Discussion

Noise reduction data were provided by Biotecture, the British company that specializes in creating living green walls. This company uses hydroponic system technologies, which is why they are the most detailed in this study, as presented in the Table 2.

Table 2. The comparative characteristics of Biotecture's green wall systems.

Parameter	Biotecture Living Wall System with Fully Planted Panels (Type 1)	Biotecture Living Wall System with Dry Panels (Type 2)	Biotecture Living Wall System with Wet Un-planted Panels (Type 3)
Description	The panels were wet with average moisture content of 60 to 70%, and were fully planted with 640 plants of a mixed perennial plant selection.	The panels were dry, excluded plants but did include the removable Grodan growing medium plugs.	The panels were wet with average moisture content of 60 to 70%, excluded plants but did include the removable Grodan growing medium plugs.
Mass per unit area of the planted panels	42 kg/m^2	10 kg/m^2	42 kg/m^2
Weighted Sound absorption coefficient (α_w)	0.75	1.00	0.5
Sound absorption class according to BS EN ISO 11654:1997 (45)	C	A	D

This table shows the sound insulation coefficient of hydroponic systems in three possible states.

We analyzed some studies which used the acoustic parametric measurements of living green wall and green roof systems [46,47]. This study examines the technological characteristics and a comparative assessment of the green wall systems based on test methods and analysis of calculated absorption parameters. The main criterion for comparing the three hydroponic systems was the sound absorption coefficient. This coefficient determines the fraction of the energy of sound oscillation absorbed by one square meter of the obstruction. The coefficient can range of values from 0 to 1, where 0—is the total reflection of the sound by the obstacle and 1—is the indicator of the total absorption of the sound.

The considered hydroponic systems have three different values of the noise absorption coefficient, which range from 0.5 to 1. Generally, type 2, containing only dry panel without plants, has slightly higher sound absorption coefficients than control samples over the entire frequency range (100–5000 Hz). This can be explained by the fact that type 2, containing only dry panel, has a more porous surface layer and a lower density.

Under the same conditions, the panels in the surface dried state have a higher absorption coefficient than the panels in the surface wetted state. Yang came to the same result in his studies [48], that a significant decrease in the absorption coefficient is observed with an increase in soil moisture. The difference in absorption coefficient between moderately dry and highly wet soil samples can be approximately in 5–10 times. Thus, it can be understood that sound absorption depends on several factors: the presence of plants on the panel and the humidity of the panel [49,50]. Previous studies have also established that vegetation itself can reduce the noise level by up to 8 dB, and sometimes more [51], that the absorption coefficient increases with frequency and vegetation coverage [52]. Thus, comparative assessment of the green wall systems based on parametric analysis [53].

4. Conclusions

Today, smart green wall and living wall solutions have become increasingly popular for their environmental, technical and aesthetic benefits. Simultaneously, existing green wall technologies can be difficult to operate. Innovative green technologies will also bring great environmental benefits and help mitigate negative impacts in the conditions of mass urban development. This study aims to understand which types of the green walls can serve as a health defense mechanism from incessant noise for people, as well as which of systems are the most beneficial to use. Three different landscaping systems were considered: felt, modular, container. In the research, we briefly examined the pros and cons of each of the green systems, but take into account more details about hydroponic system and its characteristics concerning noise absorption.

Moreover, by using the data provided to us by Biotecture, we found out which hydroponic system conditions are the most noise-absorbing. In the industrial buildings, the problem of noise pollution is more acute; thus, we suggest using greening systems in order to reduce noise levels, improve air quality and create a pleasant, lively atmosphere that will have a positive effect on the employees of the enterprise.

Thus, the results of this study are as follows:

- Various solutions of green wall systems are considered and analyzed;
- Compiled a comparative characteristic of these systems;
- The most environmentally friendly and efficient landscaping options have been identified;
- The most noise-absorbing systems have been identified.

We have found experimentally that hydroponic systems indeed reduce noise levels. It is important to note that the efficiency of the system decreases with an excessive increase in the humidity of the substrate, and also increases with an increase in the number of plants, which indicates that they also affect noise reduction. The considered hydroponic systems have three different values of the noise absorption coefficient, which range from 0.5 to 1. It can be concluded that all layers of the structure take part in reducing the noise level: plants, substrate and the structure itself.

Author Contributions: This study was designed, directed, and coordinated by N.S., E.K., E.L., D.S. and P.B. The authors contributed and proposed the theoretical model for structural and functional modeling of construction processes of green wall systems. E.K., N.S. and P.B. planned and performed the experiment for green wall systems measurements. E.L. and D.S. analyzed the measurements of sound absorption coefficients. The manuscript was written by N.S., E.K., E.L., D.S. and P.B. commented on by all authors. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: All authors declare no conflict of interest about the representation or interpretation of reported research results.

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