NATURE-BASED MOSS BARRIERS FOR URBAN NOISE ABSORPTION: IMPEDANCE TUBE ASSESSMENT OF BOREAL MOSS SPECIES

Juta Karklina, Edgars Karklins
Latvia University of Life Sciences and Technologies, Latvia
juta.karklina@lbtu.lv

Abstract. Urban noise pollution is a major environmental stressor affecting public health, well-being, and urban liveability, and is increasingly recognised as a challenge in sustainable urban transformation. While conventional noise mitigation relies on rigid, high-mass barriers, there is growing interest in nature-based solutions that simultaneously address multiple environmental pressures in cities. This study investigates the acoustic performance of living moss species as potential bio-based materials for urban noise mitigation. Four common boreal moss species, *Dicranum scoparium, Pleurozium schreberi, Hypnum cupressiforme,* and *Plagiomnium undulatum*, were experimentally assessed using an impedance tube in accordance with ISO 10534-2. Normal-incidence sound absorption coefficients were measured over the frequency range 50-1600 Hz, both for moss layers alone and in combination with a thin hemp-fibre substrate designed to support vegetative growth and optimal thickness of the material. To avoid pseudoreplication, sound absorption data were aggregated at the sample level and analysed using non-parametric methods. The results indicate species-dependent differences in acoustic performance, likely linked to moss morphology and growth form. *Pleurozium schreberi*, characterised by a thick, vertically structured weft, exhibited the highest sound absorption, reaching a peak coefficient of $\alpha = 0.62$ at 1000 Hz when combined with the hemp substrate. In contrast, species forming thin or loosely structured mats showed substantially lower absorption. The addition of the bio-based substrate was associated with increased acoustic performance across all species, particularly in mid-frequency ranges relevant to urban traffic noise. However, the overall absorption values remained within the range of lightweight porous materials, suggesting that moss alone may not function as a primary acoustic absorber. Due to the limited number of independent samples, the results should be interpreted as exploratory. Nevertheless, the findings provide new insights into species-specific acoustic behaviour of mosses and support their potential application in sustainable urban noise mitigation strategies.

Keywords: bryophytes; impedance tube; noise attenuation; noise pollution.

Introduction

Sound levels are usually expressed in decibels (dB), and due to human hearing sensitivity to certain frequencies, sound measurements often use A-weighting, noted as dBA, to reflect this. According to the World Health Organization (WHO), background noise should stay below 30 dBA to allow for restful sleep. Outdoors, sound levels above 50 dBA are generally considered disturbing [1] as the urban environment itself is an inexhaustible source of noise [2] resulting from human activities, including transport, industrial operations, and leisure activities [3]. The European Environment Agency (EEA) identifies noise pollution as one of Europe's most significant environmental health issues, with transportation noise being the leading contributor [4]. According to the WHO, road traffic noise ranks as the second most harmful environmental stressor in Europe; it impacts approximately 100 million people and creates implications on human health and well-being [5], including hypertension [6], cardiovascular disease risk, preeclampsia for pregnant women [7], and mental health as well, for example, a study in Sweden demonstrated increased cortisol levels among adolescents due to the road traffic noise, which do not impact cortisol levels directly, but annoyance of the sound of road traffic lead to worse sleep, contributing to higher cortisol levels in mornings [8]. EEA suggests reducing noise pollution sources through regulatory and legislative actions, such as reducing vehicle speed limits in urban areas, increasing the use of low-noise tires, and reducing noise from high emitters [9]. As for mitigation technologies, barrier walls and earthen berms are the main methods, typically lowering sound levels by 10-15 dBA for nearby homes. However, these solutions are costly and require ongoing maintenance. Moreover, since sound waves naturally bend around obstacles and disperse over distance, barrier walls are generally effective only within 400 meters of the roadway [10]. Therefore, it is essential not only to establish a physical barrier but also to enhance sound attenuation through the use of materials with effective acoustic absorption properties. Acoustic absorption refers to the reduction in a sound wave's amplitude as it passes through a material [11] and is measured by the amount of energy removed from the sound wave as the wave passes through a given thickness of material [12]. The efficiency of a material's sound absorption is measured via the sound absorption coefficient, represented by α, which

DOI: 10.22616/ERDev.2026.25.TF090

is defined as the ratio of absorbed sound energy to the incident energy. When a material fully absorbs sound, $\alpha = 1$. The absorption coefficient depends on the frequency of the sound, as different materials absorb various frequencies differently. The average sound absorption coefficient is used, calculated as the mean value of absorption coefficients at selected frequencies. The total sound absorption area of a surface is given by: $A = \Sigma\ (s_i \times \alpha_i)$ where si is the surface area, and αi is the sound absorption coefficient of the i-th surface [13]. To measure sound absorption properties of materials, a widely used technique is the impedance tube. It is regulated by the ISO 10534-2 standard, and this method requires a small amount of material for laboratory testing [14]. For the past decades, technical solutions for noise pollution mitigation have been searched for and sought with Green Infrastructure (GI) as a possible solution. The acoustical performance of GI encompasses two key aspects: absorbing outdoor noise and insulating indoor spaces from external sound. In urban environments, the way sound travels from noisy zones into quieter areas depends on various factors, including street width, building height, and the acoustic properties of building envelope materials. Since building façades are typically constructed from rigid materials that tend to reflect sound, there is significant potential to reduce noise diffraction by incorporating vegetation into the building envelope, enhancing its sound-absorbing capabilities [15]. Road traffic noise can also be effectively reduced through the strategic use of GI due to its sound-absorbing and scattering properties, offering a promising alternative to traditional noise barriers. However, for vegetation alone to provide meaningful noise attenuation, e.g., more than 5 dB(A), the barrier must be at least 1.5 meters thick.

A more effective approach involves combining vegetation with solid barriers [16]. For instance, a recent study evaluated the acoustic performance of various plant species, focusing on their potential to enhance noise absorption when used in GI. The study combined laboratory impedance tube tests with outdoor environment façade measurements, offering a comprehensive view of vegetation contribution to sound attenuation. The coconut fibre-humus substrate demonstrated strong sound absorption, reaching coefficients up to 0.9 at 1 kHz, with *Hedera helix* significantly enhancing performance across frequencies, while dense grass reduced absorption by approximately 40%. Field results confirmed that vegetation increased absorption by 4-20%, with species such as *Sedum album, Thymus vulgaris,* and *Carex oshimensis* providing the greatest improvements, particularly at low frequencies [17]. Another study indicated that vegetation combined with a porous substrate significantly improves acoustic performance and substrate materials like soil or coir, providing the primary sound absorption, while dense plant layers enhance absorption by increasing leaf area density and canopy thickness. Species with large, densely packed leaves oriented at varied angles perform best, particularly improving sound absorption in the mid- to high-frequency ranges (500-2000 Hz). Notably, dense ferns and combinations like *Primula vulgaris* with coir substrate showed up to 80% increased absorption at lower frequencies below 400 Hz [18]. Another study used composite materials with a layer of natural moss showing sound absorption capabilities of up to 90% [19], which is also confirmed by another recent study by Delft Technical University (Netherlands), which evaluated the sound absorption properties of six moss species applied to bioreceptive concrete surfaces. The findings indicated that moss-covered concrete enhances sound absorption, especially at frequencies above 1000 Hz. Among the moss species tested, *Polytrichum capillare* demonstrated the highest performance, achieving a peak sound absorption coefficient of 0.86 and an average of up to 0.48 across the 50-6400 Hz range [20], which shows potential for moss vegetation to act as acoustic material; nevertheless, there is a gap in knowledge of specific moss species, *Dicranum scoparium, Pleurozium schreberi, Hypnum cupressiforme,* and *Plagiomnium undulatum i*n combination with substrate material.

Therefore, this study aims to evaluate the sound absorption properties of chosen moss species using the impedance tube method, to assess their potential as natural acoustic absorbers in urban environments. This study contributes to the existing knowledge by providing species-specific acoustic characterisation of boreal mosses under controlled laboratory conditions and evaluating their interaction with a bio-based supporting substrate, which remains insufficiently explored in current literature.

Materials and methods

The measurement of absorption coefficient was performed according to ISO 10534-2 [21] in an impedance tube Brüel & Kjær Type 4206. Circular-sized moss samples in 100 mm diameter were prepared, and same sized substrate material from hemp (Figure 1).

Fig. 1. **Moss sample inside the impedance tube**

In total, there were eight samples tested, of which four were without any substrate: D.s-NH, H.c-NH, P.u-NH, P.s-NH, remaining four were with hemp substrate: D.s-H, H.c-H, P.u-H, P.s-H (Table 1). For the first tested species (D.s-H and D.s-NH), measurements were conducted in triplicate, with the sample reinserted into the impedance tube before each trial. As the results showed high reproducibility with no observable variation, subsequent measurements for each following species were performed as single trials to streamline the experimental procedure.

Table 1

Moss samples tested

Short name	**Species**	**Substrate**	**Thickness (cm)**	**Density**
D.s-H	*Dicranum scoparium*	Hemp mat	5.0	High
D.s-NH	*Dicranum scoparium*	No	4.5	High
H.c-H	*Hypnum cupressiforme*	Hemp mat	2.2	Medium
H.c-NH	*Hypnum cupressiforme*	No	1.7	Medium
P.u-H	*Plagiomnium undulatum*	Hemp mat	3.0	Very low
P.u-NH	*Plagiomnium undulatum*	No	2.5	Very low
P.s.-H	*Pleurozium schreberi*	Hemp mat	8.5	Low
P.s.-NH	*Pleurozium schreberi*	No	8.0	Low

The frequency inside the impedance tube was limited to 50-1600 Hz range, with two microphones for the transfer function method, which were calibrated before the measurements. Environmental conditions during the tests were $T = 23.2$°C, humidity 51% (Figure 2).

Fig. 2. **Four moss samples and substrates, impedance tube, and meteorological station**

Statistical analyses were performed in R (R Core Team, 2024). Before analysis, the dataset structure was evaluated. As multiple sound absorption measurements were obtained across frequency bands for each sample, these data represent repeated measurements rather than independent observations. Therefore, to avoid pseudoreplication, sound absorption coefficients were aggregated at the sample level by calculating mean values for each specimen. An exploratory assessment of residuals from preliminary parametric models revealed deviations from normality and heterogeneity of variances. Consequently, non-parametric statistical methods were applied. Differences in sound absorption among moss species and substrate conditions were evaluated using the Kruskal-Wallis test. Due to the limited number of independent samples, interaction effects were not tested statistically and were instead assessed descriptively.

To contextualise the experimental results, typical absorption coefficients of commonly used building materials were compiled from literature sources [22-27]. These values provide a practical benchmark for evaluating the relative performance of the tested materials across frequency ranges (Table 2).

Table 2

Typical sound absorption coefficients of common building materials (adapted from literature)

Material	500 Hz	1 kHz	2 kHz
Concrete	~0.04	~0.06	~0.08
Brick	~0.03	~0.04	~0.05
Acoustic panels	~0.6-0.9	~0.7-0.9	~0.8-1.0

In conclusion, the applied methodology provides a solid basis for further research. Future studies should incorporate a greater number of specimens and repeated measurements to enhance reliability and enable broader-scale application.

Results and discussion

The acoustic performance of the tested moss species was evaluated through analysis of sound absorption coefficients under varying substrate conditions and across a range of frequencies. The small number of independent samples limits the study. Although multiple measurements were obtained across frequency bands, these represent repeated observations of the same specimens rather than independent replicates. Therefore, statistical analyses should be interpreted as exploratory, and further studies with increased replication are required to confirm the observed trends.

The table (Table 3) summarises the experimentally obtained sound absorption coefficients of the tested moss samples at selected frequencies.

Table 3

Sound absorption coefficients of tested moss samples at selected frequencies

Short name	500 Hz	1 kHz	1.6 kHz
D.s-H	0.11	0.24	0.46
D.s-NH	0.08	0.17	0.32
H.c-H	0.09	0.19	0.38
H.c-NH	0.07	0.12	0.23
P.u-H	0.09	0.21	0.47
P.u-NH	0.06	0.11	0.22
P.s.-H	0.31	0.62	0.54
P.s.-NH	0.31	0.49	0.48

The results presented in the table depict a consistent increase in sound absorption coefficients with increasing frequency across all tested samples. This trend is particularly evident between 500 Hz and 1.6 kHz, where most specimens exhibit a gradual rise in absorption performance. Among the tested samples, noticeable differences can be observed between species and treatment conditions. Samples that had a hemp substrate (labelled as H) generally demonstrate higher absorption values compared to samples without substrates (labelled as NH), indicating the enhancement of absorption when a substrate in use. The highest absorption values were recorded for the *Pleurozium schreberi* (P.s. samples, particularly P.s.-H), which reached 0.62 at 1 kHz and maintained relatively high performance at 1.6 kHz. On the contrary, samples such as P.u.-NH and H.c.-NH exhibited lower absorption values across all frequencies, indicating more limited acoustic effectiveness. The relatively small variation at lower frequencies (500 Hz) suggests that all samples behave similarly in this range, with more pronounced differentiation emerging at higher frequencies.

Further analysis was conducted using mathematical statistics methods, and non-parametric analysis indicated variability in acoustic performance across species, supporting the observed trends in the experimental data. Aggregated sample-level analysis revealed clear differences in mean sound absorption among the investigated moss species (Fig. 3). While aggregated analysis was used for statistical evaluation, frequency-dependent behaviour remains an important characteristic of acoustic performance and is discussed qualitatively.

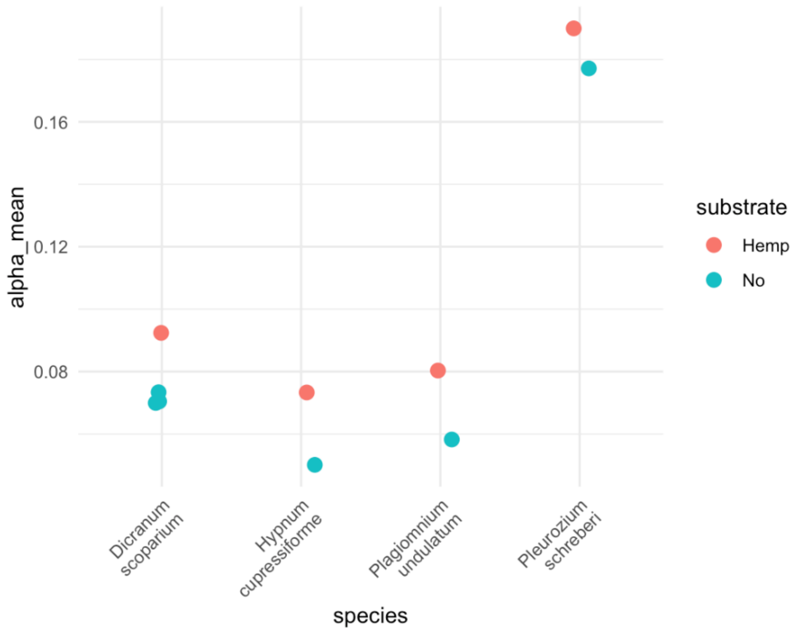

Fig. 3. **Mean sound absorption coefficient (*α*) of moss samples aggregated at the specimen level for each species and substrate condition. Points represent individual samples, with colours indicating substrate type (hemp-supported and non-supported)**

Among all tested samples, *Pleurozium schreberi* (P.s.-H and P.s.-NH) exhibited the highest mean absorption coefficients under both substrate conditions. In contrast, *Hypnum cupressiforme* and *Plagiomnium undulatum* showed comparatively lower absorption values, while *Dicranum scoparium* demonstrated intermediate performance. Across all species (D.s-H, H.c-H, P.u-H, and P.s.-H), the presence of the hemp-based substrate was associated with increased mean sound absorption coefficients. This trend was consistent for each species. Differences in acoustic performance among the tested moss species can be attributed to their morphological and structural characteristics (as listed in Table 1). Species with thicker, more vertically oriented shoots and higher internal porosity, such as *Pleurozium schreberi*, are likely to enhance sound attenuation through increased air-material interaction and energy dissipation. In contrast, species forming thinner or more loosely structured mats provide fewer internal interfaces for sound wave scattering, resulting in lower absorption efficiency. The observed improvement in sound absorption with hemp substrate can be explained by the additional porous structure introduced beneath the moss layer. This composite system likely enhances acoustic performance by increasing tortuosity and internal friction, thereby improving dissipation of sound energy, particularly in mid-frequency ranges.

To contextualise the obtained results, the measured sound absorption coefficients (Table 3) were compared with typical values reported for conventional building materials (Table 2). At lower frequencies (500 Hz), the tested moss samples exhibited relatively low absorption, with values generally exceeding those of dense materials such as concrete and brick, but remaining within the range of lightweight natural materials such as wood or textiles ($\alpha \approx 0.05$-0.20). As frequency increased to 1 kHz, a noticeable improvement in absorption performance was observed across all samples, indicating enhanced interaction between the porous moss structure and incident sound waves. At higher frequencies (1.6 kHz), several samples demonstrated a substantial increase in sound absorption, with the best-performing specimens reaching values above 0.5. In particular, *Pleurozium schreberi* samples exhibited the highest performance, approaching the lower range of conventional porous acoustic materials, although still below the typical performance of engineered acoustic panels.

The results suggest that moss-based systems have potential as bio-based sound-absorbing materials, especially in mid-to-high frequency ranges. However, it should be noted that the comparison with literature data is indicative, as differences in measurement methodology and frequency ranges limit direct equivalence.

Conclusions

1. In the presented study, the sound absorption of moss-based samples is species-dependent, with *Pleurozium schreberi* demonstrating the highest absorption capacity.
2. The addition of a hemp-based substrate enhanced acoustic performance and reduced variability in sound absorption.
3. Sound absorption coefficients increased with frequency, indicating that moss-based systems are more effective in attenuating mid- to high-frequency noise.
4. Differences between moss species and substrate conditions suggest that structural and morphological characteristics influence acoustic behaviour; however, these findings should be interpreted cautiously due to limited sample replication.
5. Moss-based materials demonstrate potential as bio-based sound absorbers, with performance influenced primarily by species morphology and supported by substrate integration.

Acknowledgements

Experimental work was conducted at the Riga Technical University, Institute of High-Performance Materials and Structures, under the guidance and supervision of Dr. sc. ing. Deniss Mironovs. Species selection and material sampling were supervised by Dr. biol. Līga Strazdiņa. The experimental work was carried out in collaboration with Edgars Kārkliņš (PhD student in Environmental Engineering, Latvia University of Life Sciences and Technology). Data analysis, as well as the literature review and interpretation of results, were performed by Juta Kārkliņa as part of her broader doctoral research at the Environmental Engineering PhD program at the Latvia University of Life Sciences and Technology on mosses as providers of ecosystem services, including sound absorption.

Author contributions:

Conceptualization, J.K.; methodology, J.K.; software, J.K.; validation, J.K.; formal analysis, J.K.; investigation, J.K. and E.K.; data curation, J.K.; writing – original draft preparation, J.K.; writing – review and editing, J.K. and E.K.; visualization, J.K.; project administration, J.K. All authors have read and agreed to the published version of the manuscript.

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