

Article

Sound Absorption of Hydroponically Grown Plants

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Abstract: Hydroponics is a method of growing plants without soil and serves as an efficient agricultural production system. Compared to traditional farming, hydroponic crops offer significant water savings while also reducing the need for chemical pesticides by eliminating soil-borne diseases and pests. Additionally, hydroponic materials are being studied as a potential food source for space missions and as a substitute for industrially produced animal feed during winter. This paper explores the acoustic absorption properties of green materials derived from hydroponic systems. The roots of wheat grown in a porous layer formed a rigid skeleton structure. After drying, test specimens were prepared for acoustic measurements, undertaken using an impedance tube, to assess the material’s sound absorption performance. The results indicate optimal absorption around 600 Hz and 2000 Hz, reaching $\alpha = 0.95$ – 1.0 , which is significant. A brief description of the substrate layers is also provided.

Keywords: hydroponic systems; acoustic measurements; acoustic absorption; green tiles; sustainability; eco-constructions



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1. Introduction

Sustainable materials, also known as green materials, have been increasingly utilized in recent decades for constructing building fabrics. These materials are primarily employed to comply with regulations on energy savings and carbon dioxide (CO₂) emission limits, particularly in the case of thermal insulation [1]. More recently, sustainable materials have also been applied in architectural acoustics as substitutes for traditional sound-absorbing materials such as glass wool, polyester, and foams. A key advantage of sustainable materials is their recyclability without harming the environment. Eco-compatible materials, derived from natural sources such as animals, plants, and minerals, are free from chemical additives [2]. As a result, they do not emit pollutants harmful to the environment or human health. These materials are also recyclable, biodegradable, and require low energy consumption throughout their life cycle [3]. The construction sector is increasingly adopting eco-compatible materials, driven by regulatory restrictions on energy consumption and environmental impact. These materials also provide significant benefits for acoustic performance [4,5]. National regulations for public construction projects increasingly encourage their use, further promoting their absorption in the industry.

Many researchers have published studies on green materials [6], highlighting their newly discovered functions, including high acoustic absorption—particularly at high frequencies—comparable to traditional porous materials. Generally, green materials are

triturerated or mixed with other components and require a rigid skeleton to function effectively as porous materials [7,8]. Previous research studies by Berardi [9] have reported absorption coefficient values for materials such as kenaf, wood fibers, hemp [10], coconut, cork, mixed cane, and cardboard [11]. These fiber-based materials show a linear, ever-increasing absorption coefficient trendline. However, when green tiles have a granulated composition (e.g., wood, canes), their absorption trendline exhibits two peaks. Absorption coefficients have also been measured for broom-based tiles. Broom plants, commonly found in Mediterranean regions, were cut and shredded to prepare multiple samples. The results were promising, especially above 500 Hz, where samples consistently showed normal sound absorption above 0.5. The absorption coefficients for straw, hay, broom, plant litter, coarse-grained chestnut, wood chips, and fine-grained poplar wood chips show a double-peak trendline, with maximum peaks recurring at constant intervals based on material thickness [12,13]. Since these green materials are loose and granular, some manufacturers have packed them in jute envelopes to create absorption panels for reducing reverberation in classrooms [14], as shown in Figure 1.



Figure 1. Jute envelopes wrapping the absorption panels (a) and application of absorption coefficients in classrooms (b).

Hydroponics is a method of growing plants without soil and serves as an efficient agricultural production system. Compared to traditional farming, hydroponic crops offer significant water savings while also reducing the need for chemical pesticides by eliminating soil-borne diseases and pests.

Hydroponic systems help reduce soil degradation and erosion, contributing positively to sustainable land use. This technique utilizes sublayers of alternative materials such as expanded clay, rock wool, perlite, paper, hemp, wood chips, and natural wool, combined with nutrient solutions or water.

A key advantage of hydroponic systems is their ability to produce large quantities of fruits or flowers in a much shorter time compared to traditional soil-based cultivation. These systems are primarily developed to provide animal feed as an alternative to synthetic or chemical-based options. Additionally, hydroponic cultivation is being explored as a potential food source for future space missions [15]. In such contexts, plants provide essential calories for humans while also supporting natural processes. Throughout their life cycle, plants produce oxygen, absorb carbon dioxide through photosynthesis, and generate potable water via transpiration.

The study of hydroponic systems for food is crucial in addressing the challenges posed by climate variability, population growth, and fresh water depletion. In these circumstances, alternative food production in controlled environments becomes essential to ensure food security in a changing world [16]. In the future, hydroponic cultures could also be employed in regions with scarce natural resources, where extreme conditions make traditional agriculture unfeasible.

Historically, hydroponic cultivation has played a role in Christian Easter traditions since the Middle Ages. It has been used to grow decorative plants for church altars. During Easter, natural ornaments made from wheat grown on paper or jute sublayers, cultivated in the absence of light, are created. This lack of light gives the plants a characteristic yellowish color due to the absence of chlorophyll. The final product consists of green tiles featuring wheat plants that grow to a height of 20–30 cm, as shown in Figure 2.



Figure 2. Christian church altar decoration during Easter: particular detail (a), overall scenography composition (b).

The hydroponic material model was designed to create layers of sound-absorbing materials. In this study, wheat was chosen, but other plants such as corn, chickpeas, beans, or grasses like *gramilla* could be used. As the seed germinates, the plants develop on the surface, while the roots penetrate the porous layer beneath, generating a rigid network that compacts the substrate.

The objective of this research is to develop plant-based sound-absorbing materials using hydroponic systems. Layers of varying thicknesses were developed with different porous materials, serving as substrates for wheat growth. The wheat grains were cultivated at room temperature and watered daily with small amounts of water. The material was inserted in food-grade plastic containers and kept outdoors, where the temperature ranged from approximately 18 °C at night to 35 °C during the day.

The porous materials used as substrates were as follows:

- Hemp;
- Triturated paper
- Wood chips;
- Triturated sugar canes from river water.

Over two weeks, the wheat grew to a height of 20 cm. During this process, the roots penetrated the porous substrates, forming a compact material with a rigid skeleton. Once dried, the water component was completely removed, resulting in a material with optimal acoustic properties.

Various acoustic tests were conducted on the resulting green tiles, which were based on different porous sublayers [17,18]. Samples with a diameter of 10 cm and thicknesses ranging from 5 to 10 cm were prepared for testing. The primary aim of this research is

to assess the absorption coefficient of these tiles at different thicknesses. The tests were conducted using an impedance tube, which measures sound absorption coefficients at normal incidence across a frequency range of 100 Hz to 2000 Hz.

2. Materials and Methods

When a sound wave hits the surface of a sample under test, the sound energy is partially absorbed, partially reflected, and the remaining portion is transmitted through the material. The absorption coefficient is therefore expressed as the ratio of absorbed and transmitted energy to the incident wave. Sound absorption tests can be conducted with an impedance tube. Given the known acoustic impedance of a material, it is possible to determine its absorption coefficient.

Another factor influencing the absorption characteristics of a material is airflow resistivity, which depends on the density of the fibers and specific flow resistivity. It is also important to note that the bulk density is related to porosity, tortuosity, and viscosity of a material.

The measurements using the impedance tube were conducted with two microphones placed along the longitudinal axis. The absorption coefficient, which ranges from 0 to 1, quantifies the amount of sound energy absorbed by a material. A coefficient value close to 0 indicates that the material reflects most of the incident sound, while a value close to 1 signifies that the material absorbs most of the incident sound energy [19–22].

The sound absorption coefficient at normal incidence was determined according to the procedure described in the ISO 10534-2 [23], with the transfer function method. For normal incidence measurements, an impedance tube (Kundt's tube) was used. The impedance tube had the following characteristics: an internal diameter of 10 cm (corresponding to an upper frequency limit of 2000 Hz), a length of 56 cm, and two $\frac{1}{4}$ " microphones, placed 10 cm apart for measurements starting from 100 Hz.

To obtain reliable values of the absorption and minimize the effects of sample irregularities, four separate measurements were performed on each sample. The resulting absorption values represent the average of these four measurements. The standard deviation corresponds to <2%, and for this reason, it has been considered negligible.

The static airflow resistance ($\text{N}\cdot\text{s}\cdot\text{m}^{-4}$) was measured in accordance with the international standard ISO 9053-2 [24]. Measurements were carried out using the alternate flow method at a frequency of 2.0 Hz. The testing device consisted of a cylindrical tube with an internal diameter of 10 cm, sealed with the sample material. A piston system, driven by a rotating cam, generated an alternating airflow inside the tube, while a microphone measured the pressure disturbance. The SCS 9023 system forced air from the reciprocating motion of a piston that moves at a frequency of 2 Hz; the internal pressure was measured with a special microphone system. Knowing the density of the compact material and the density of the hydroponic material, the porosity (Y) was determined. The apparent density ρ_m (kg/m^3) was evaluated by weighing different material volumes into a graduated glass tube, while the density of the solid ρ_{solid} (kg/m^3) was obtained by weighing the uncrushed material. Table 1 shows the density, porosity, and flow resistivity values. In this specific case, since the material is porous and easy to handle, and based on experience acquired over the years, measurements were carried out only once.

Table 1. Density, porosity, and flow resistance values.

Materials	Density of Hydroponic Material ρ (kg/m^3)	Porosity Y (%)	Static Airflow Resistance ($\text{N}\cdot\text{s}\cdot\text{m}^{-4}$)
Hydroponic on hemp substrate	34	0.97	$1.6\cdot 10^5$
Hydroponic on substrate of triturated paper	100	0.65	$2.7\cdot 10^5$

Table 1. Cont.

Materials	Density of Hydroponic Material ρ (kg/m ³)	Porosity γ (%)	Static Airflow Resistance (N·s·m ⁻⁴)
Hydroponic on substrate of wooden chips	85	0.95	$5.3 \cdot 10^5$
Hydroponic on triturated canes	145	0.85	$2.4 \cdot 10^5$

Materials

Natural fibers can originate from three sources: animal, cellulose, and mineral. In this study, only the cellulose-based fibers are considered, in particular wood fibers in the form of sugarcane from river water and wheat grains from the stalk, jute, and hemp from the bast [25,26]. The recycled material used in this study is paper.

The trituration of paper and sugarcane was necessary to enable the wheat grains to extend their roots across the substrate, thereby forming a very compact and solid composite once dried. Figure 3 shows the growth of green tiles based on different substrates.

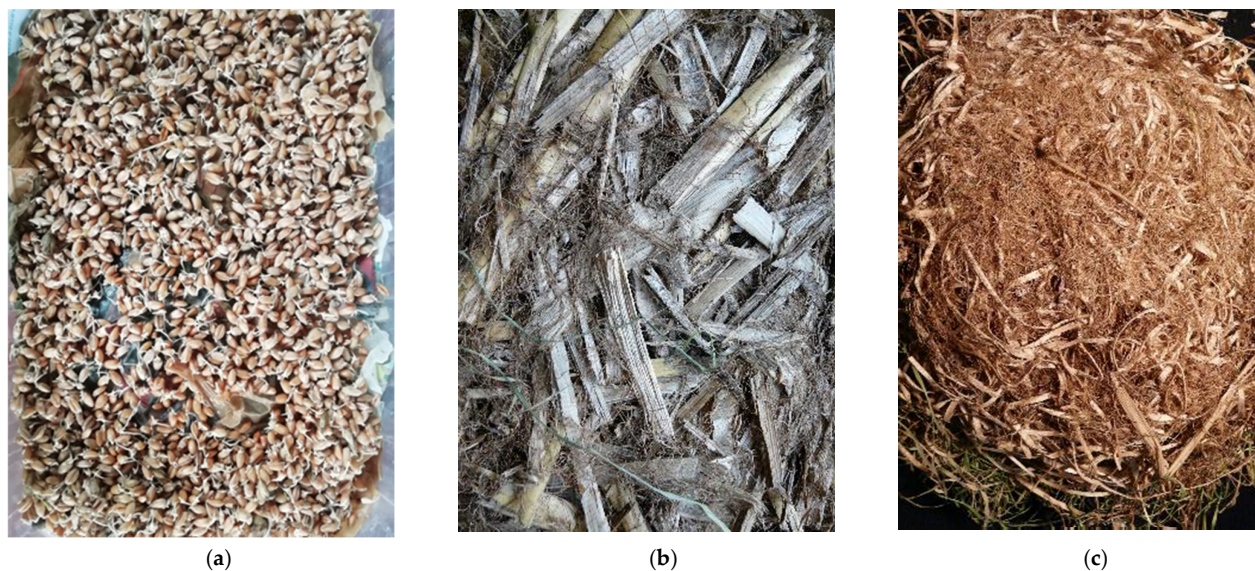


Figure 3. Cultivation of wheat grains on substrate of paper (a), grains on triturated sugar canes (b), and grains on hemp (c).

Once the wheat grains have germinated and grown in the pots, their roots bind the substrates, regardless of whether they consist of small or large particles, creating a pure green tile [27], as shown in Figure 4.

Figure 5 shows the impedance tube used for acoustic measurement (SCS—SCS 902A); the two microphones were BSWA Tech model MPA416, while the sound amplifier was Nobsounds model NS-10G. After the hydroponic material has grown, creating layers with a rigid skeleton, it is dried and placed in cylinders to create measurement samples.

Figure 6 shows the SCS 9023 system for the flow resistance measurements; it is composed of a 100 mm cylinder, holding a low-frequency pressure wave source, a low-frequency response $\frac{1}{2}$ " microphone, and an adjustable sample holder. The low-frequency pressure wave is generated by means of a piston, which is an alternating displacement driven by a 10:1 geared motor and an electronic, closed-loop speed controller. Further to the standard reference flow speed, three different flow speeds may be generated by simply substituting one of the four calibrated cams on the geared motor shaft.

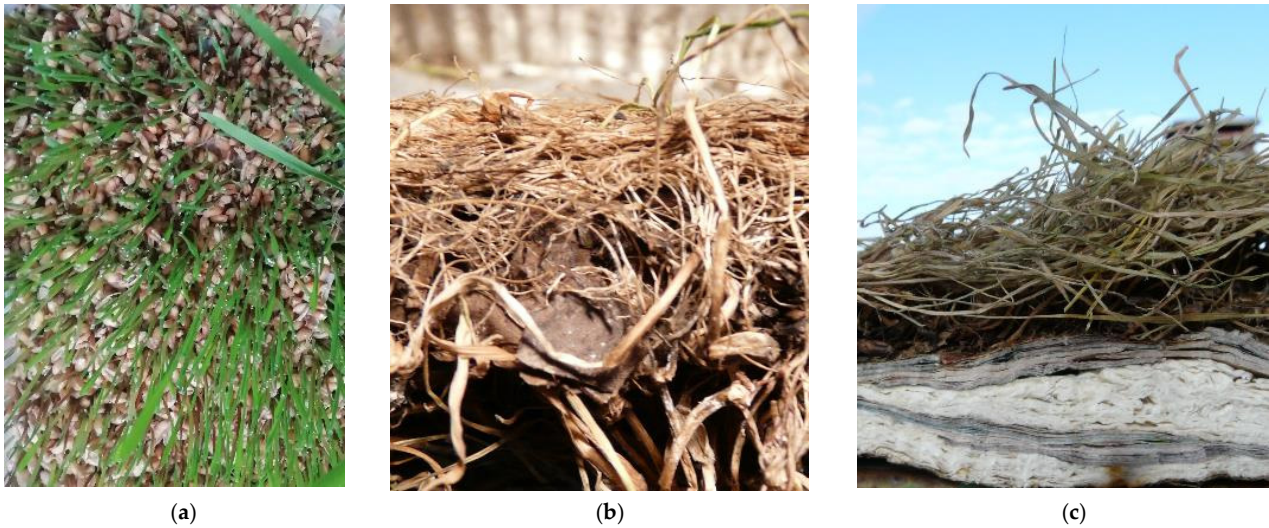


Figure 4. Wheat growth (a), substrate of wood chips (b), and trituated paper substrate (c).



Figure 5. Impedance tube by SCS—SCS 902A.

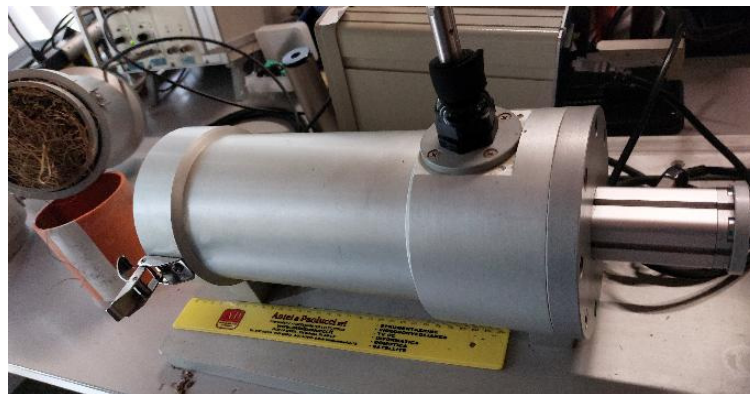


Figure 6. SCS 9023 system for flow resistance measurements.

Figure 7 shows the hydroponic samples used for sound absorption measurements with the impedance tube. The measuring tube has a circular cross-section with a diameter of 10 cm; therefore, the samples are prepared by inserting the material into plastic cylinders. For each type of material, two thicknesses, 5 cm and 10 cm, were prepared by inserting the test material inside plastic pots of the desired dimensions. This approach allows for the evaluation of the acoustic absorption coefficient as a function of thickness.



Figure 7. Hydroponic material samples ready for impedance tube measurements (5 cm and 10 cm thicknesses).

3. Results

Acoustic measurements were performed on samples with thicknesses of 5 cm and 10 cm to evaluate sound absorption as a function of thickness and frequency [27,28]. The results of the absorption tests are summarized in the following figures.

Figure 8 shows the absorption performance of the hemp material (black line: 5 cm thickness, red line: 10 cm thickness). The highest absorption coefficient is found at 2000 Hz for the 5 cm thick substrate and at 800–1000 Hz for the 10 cm thick substrate. As the thickness of the sample increases, the maximum value of sound absorption shifts towards low frequencies; this is a characteristic behavior of porous material on a rigid wall. However, the highest absorption values remain around 0.55.

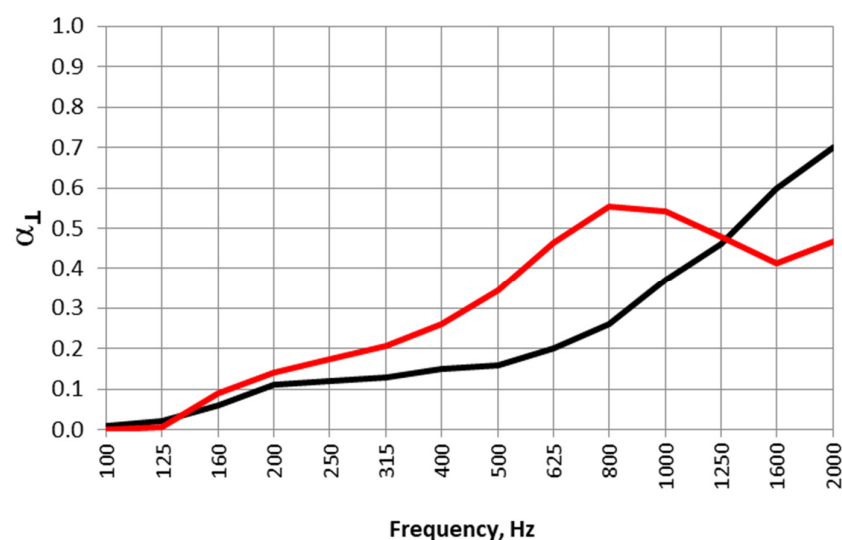


Figure 8. Absorption coefficients related to hemp (black line: 5 cm thickness, red line: 10 cm thickness).

Figure 9 shows the absorption coefficient when the hydroponic substrate is made of hemp (black line: 5 cm thickness, red line: 10 cm thickness). For samples with 5 cm thickness, the highest values around 0.55 are observed at 2000 Hz. When the thickness increases to 10 cm, the highest values, around 0.60, occur at approximately 800 Hz.

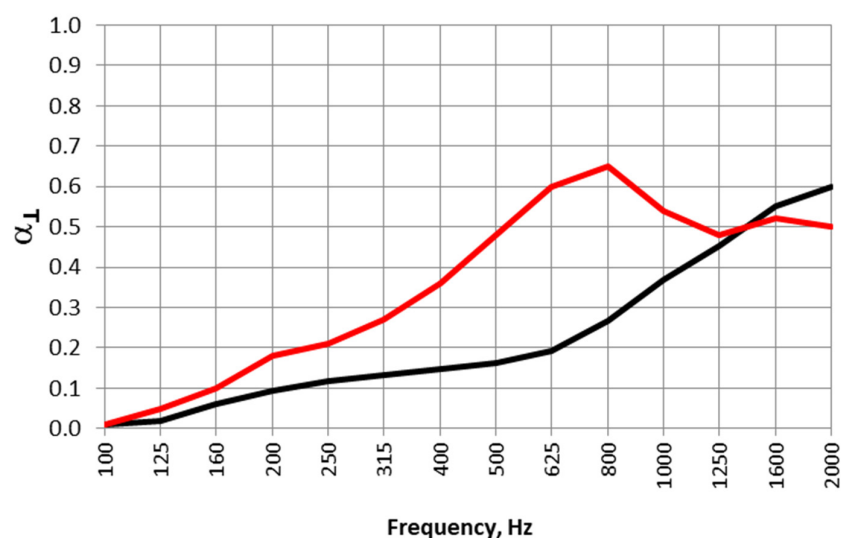


Figure 9. Absorption coefficients of hydroponic system grown on hemp substrate (black line: 5 cm thickness, red line: 10 cm thickness).

As in the previous case, increasing the sample thickness shifts the acoustic absorption toward mid to low frequencies. However, the absorption performance at low frequencies remains low, close to zero.

When the hydroponic substrate consists solely of triturated paper, the absorption coefficients are highly effective, reaching a value of 1.0 at 500 Hz for a 5 cm thickness and at 250 Hz and 800 Hz for a 10 cm thickness, as shown in Figure 10.

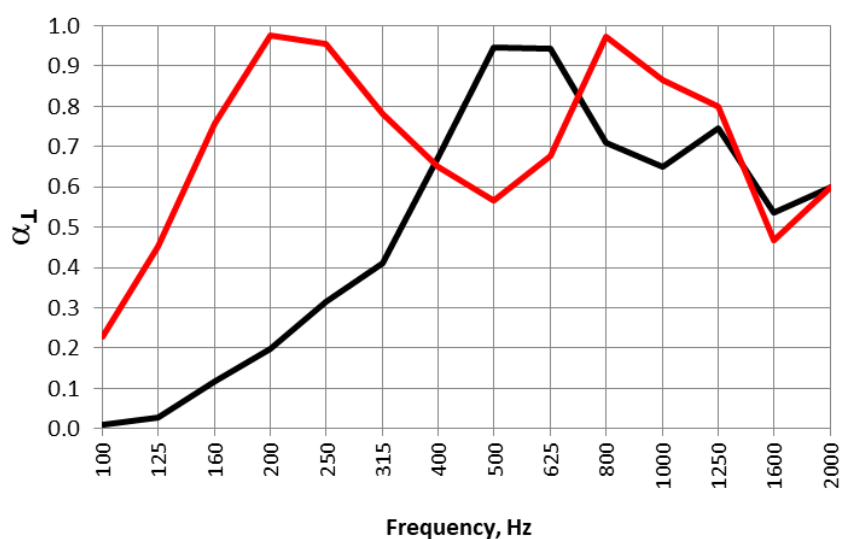


Figure 10. Absorption coefficients related to the substrate of triturated paper, with different thicknesses (black line: 5 cm thickness, red line: 10 cm thickness).

This is a remarkable result that can challenge any other traditional absorbing panel, as improving performance at low frequencies typically requires a significant increase in thickness. The green material demonstrates very promising results, achieving high absorption efficiency with a maximum thickness of just 10 cm [29–33].

In a similar way, the absorption coefficients obtained with a hydroponic substrate composed of triturated paper show a peak performance centered on high frequencies, specifically around 1000 Hz for a 5 cm thickness and at 500 Hz for a 10 cm thickness. The peak values range between 0.95 and 1.0, as shown in Figure 10.

When the substrate consists of hydroponic wood chips, as shown in Figure 11, the absorption performance does not improve for a thickness of 5 cm. In case of a substrate of sugarcane, the peak values with a thickness of 10 cm reach a value of 0.86 at 500 Hz and 0.96 at 1600 Hz, as shown in Figure 12, while the results related to 5 cm thickness are similar to the others previously discussed.

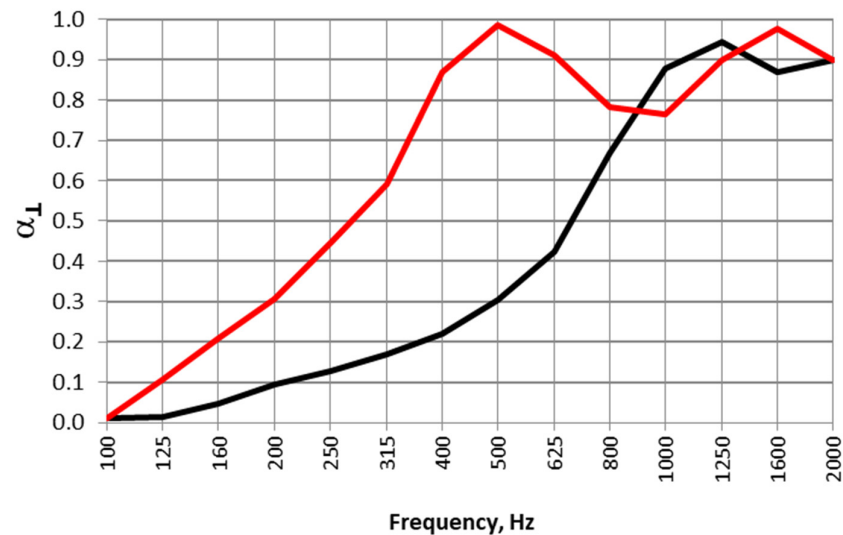


Figure 11. Absorption coefficients related to the substrate wood chips (black line: 5 cm thickness, red line: 10 cm thickness).

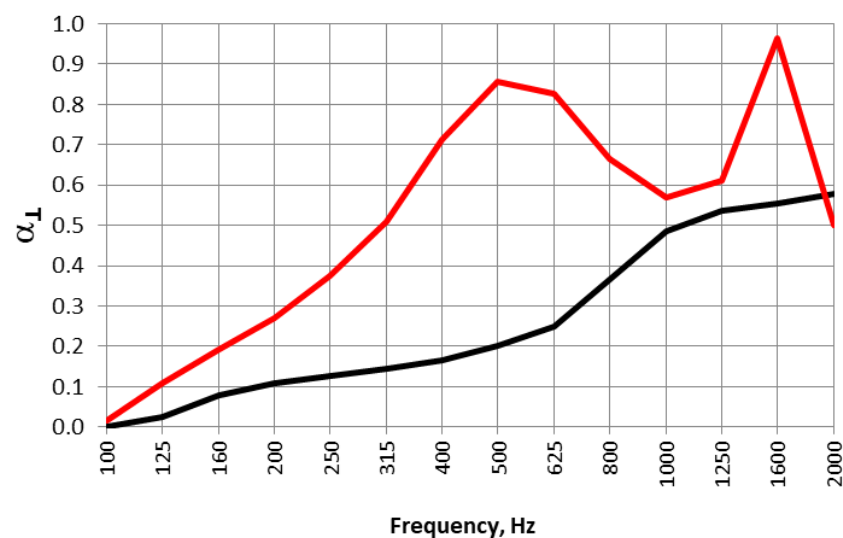


Figure 12. Absorption coefficients related the substrate of trituated canes from river water, (black line 5 cm thickness, red line 10 cm thickness).

4. Discussion

The hydroponic system enables plant growth without soil consumption. This technique is used to create rigid skeleton-like materials from granulated compositions dissolved in water. In this study, wheat grains were grown on a granular substrate, allowing the roots to penetrate the granulated material and form a rigid skeleton.

The increase in microcavities makes these green tiles highly porous and, therefore, more acoustically absorbent. Based on the results reported in the previous section, hydroponically grown green materials appear to be a promising alternative to the decreasing availability of soil due to rapid urbanization. This type of material can be used for systems requiring sound absorption and noise reduction; it can be used inside plant barriers to

reduce the reflection of sound in the surrounding environment, but it has a low transmission coefficient value and cannot be used in conditions where adequate sound insulation is desired.

Below are the measurements trends categorized by thicknesses of 5 cm and 10 cm, allowing for a comparison of differences in materials. The materials tested are as follows:

- Hemp alone;
- Hemp hydroponic substrate;
- Triturated paper hydroponic substrate;
- Wood chips hydroponic substrate;
- Triturated canes hydroponic substrate.

Figure 13 illustrates the trend for 5 cm thickness, while Figure 14 presents the trend for 10 cm thickness. The same results are numbered in Table 2. Notable differences are primarily in the hemp and hydroponic hemp layer, whereas the other materials show variations in the absorption coefficient values.

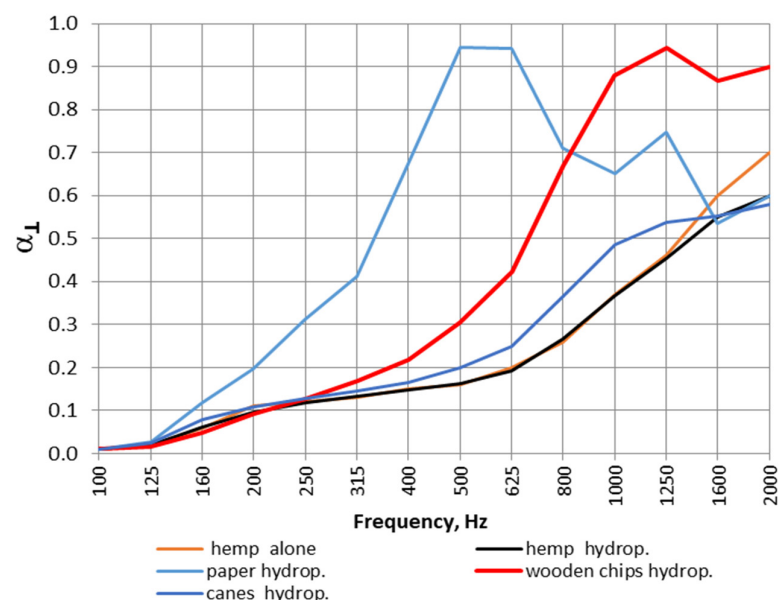


Figure 13. Absorption coefficients related to 5 cm sample thickness.

In summary, the best absorption coefficients were observed with a 10 cm thickness, particularly when paper and wood chips were used as substrates, achieving values between 0.95 and 1.0 across two frequency bands, as shown in Figure 13.

The newly developed sound-absorbing materials derived from hydroponically grown wheat exhibit behavior like traditional porous materials. Thin layers do not absorb well at low frequencies, whereas increasing the material thickness enhances sound absorption at lower frequencies.

The acoustic absorption measurements were obtained using an impedance tube, with the porous material placed on the rigid surface of the tube's end. Acoustic absorption could be increased by creating a back cavity between the material and the rigid back wall.

This paper presents, for the first time, the acoustic application of hydroponic material created by sowing wheat on porous layers of loose granular material. Future research should explore different types of seeds, such as beans, chickpeas, and couch grass, whose roots can form a rigid skeleton. Additionally, this research should be integrated into the food supply chain sector to achieve dual benefits: food production and the development of green materials for acoustic panels. The acoustic characteristics of hydroponic materials depend on the fact that the material has microcavities that allow the attenuation of the

incident sound and therefore obtain a suitable acoustic absorption. The variations in the absorption coefficient with frequency depend on the interactions of the sound inside the material and the relative thickness. Future studies could provide more indications to improve the acoustic absorption by varying the prosthesis and the resistance to the flow.

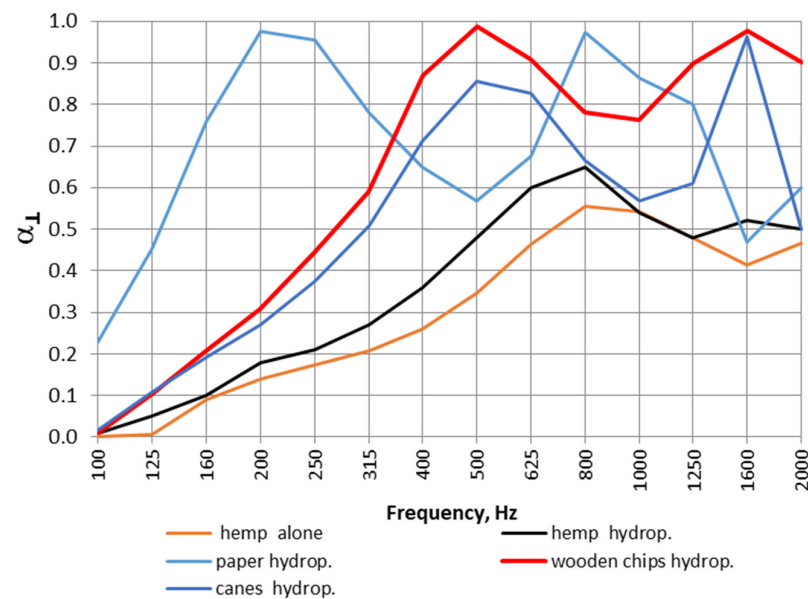


Figure 14. Absorption coefficients related to 10 cm sample thickness.

Table 2. Tabulated data of absorption coefficients related to 5 cm and 10 cm sample thicknesses.

Test Sample	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz
<i>5 cm thickness samples</i>					
Hemp	0.02	0.11	0.16	0.36	0.60
Hemp hydroponic	0.02	0.12	0.16	0.37	0.70
Triturated paper hydroponic	0.02	0.31	0.95	0.65	0.60
Wood chip hydroponic	0.02	0.12	0.30	0.88	0.90
Triturated cane hydroponic	0.02	0.13	0.2	0.49	0.58
<i>10 cm thickness samples</i>					
Hemp	0.05	0.21	0.48	0.54	0.50
Hemp hydroponic	0.01	0.17	0.35	0.54	0.47
Triturated paper hydroponic	0.45	0.95	0.57	0.86	0.60
Wood chip hydroponic	0.10	0.44	0.99	0.76	0.90
Triturated cane hydroponic	0.10	0.38	0.86	0.57	0.50

5. Conclusions

The sustainable concept of preserving soil for agriculture can be effectively explored through hydroponic systems. To date, hydroponic systems have not been widely used for interior design or architectural finishes. However, this study demonstrates the functionality of green tiles in terms of absorption.

In particular, the absorption coefficients are tuned to specific frequency bands, reaching 2000 Hz with 5 cm thickness and shifting to around 600 Hz with 10 cm thickness. The absorption magnitude in these cases reaches values between 0.95 and 1.0, especially when using triturated paper or wood chips as substrates.

A significant change in architectural design is possible by adopting strategies that reduce CO₂ emissions and incorporate local, recycled materials aligned with the sustainability principles. Future research studies will focus on applying these green tiles to real

case studies by measuring the reverberation before and after installation. Additionally, potential applications for impact noise reduction could be explored, particularly for green roofs and penthouses, where terraces are often designed with trees and plants.

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Conflicts of Interest: Giovanni Amadasi was employed by SCS-ControlSys—Vibro-Acoustic company. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Arenas, J.P.; Crocker, M.J. Recent trends in porous sound absorbing materials for noise control. *Sound. Vib.* **2010**, *44*, 12–17.
2. Putra, A.; Abdullah, Y.; Efendy, H.; Farid, W.M.; Ayob, R.; Py, M.S. Utilizing Sugarcane Wasted Fibers as a Sustainable Acoustic Absorber. *Procedia Eng.* **2013**, *53*, 632–638. [\[CrossRef\]](#)
3. Büyükakinci, Y.; Sökmen, N.; Küçük, H. Thermal conductivity and acoustic properties of natural fiber mixed polyurethane composites. *Tekst Konfeksiyon* **2011**, *21*, 124–132.
4. Peng, L.; Song, B.; Wang, J.; Wang, D. Mechanic and Acoustic Properties of the Sound-Absorbing Material Made from Natural Fiber and Polyester. *Adv. Mater. Sci. Eng.* **2015**, *2015*, 274913. [\[CrossRef\]](#)
5. Yang, W.; Li, Y. Sound absorption performance of natural fibers and their composites. *Sci. China Technol. Sci.* **2012**, *55*, 2278–2283. [\[CrossRef\]](#)
6. Biagiotti, J.; Puglia, D.; Kenny, J.M. A review on natural fiber-based composites part I: Structure, processing and properties of vegetable fibres. *J. Nat. Fiber.* **2004**, *1*, 37–68. [\[CrossRef\]](#)
7. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, Amending Directives 2009/125/EC and 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC. Available online: <http://eur-lex.europa.eu/legal-content/en/TXT/?uri=celex:32012L0027> (accessed on 23 February 2025).
8. Pervaiz, M.; Sain, M. Carbon storage potential in natural fiber composites. *Resour. Conserv. Recy.* **2003**, *39*, 325–340. [\[CrossRef\]](#)
9. Berardi, U.; Iannace, G. Acoustic characterization of natural fibers for sound absorption applications. *Build. Environ.* **2015**, *94*, 840–852. [\[CrossRef\]](#)
10. Iannace, G.; Ciaburro, G.; Trematerra, A. Modelling sound absorption properties of broom fibers using artificial neural networks. *Appl. Acoust.* **2020**, *163*, 107239. [\[CrossRef\]](#)
11. Atalla, N.; Panneton, R.; Sgard, F.; Olny, X. Acoustic absorption of macro-perforated porous materials. *J. Sound Vib.* **2001**, *243*, 659–678. [\[CrossRef\]](#)
12. Fouladi, M.H.; Nassir, M.H.; Ghassem, M.; Shamel, M.; Peng, S.Y.; Wen, S.Y.; Xin, P.Z.; Mohd Nor, M.J. Chapter 7: Utilizing Malaysian natural fibers as sound absorber. In *Modeling and Measurement Methods for Acoustic Waves and for Acoustic Microdevices*; Beghi, M.G., Ed.; InTech: Rijeka, Croatia, 2013; pp. 161–170.
13. Asdrubali, F.; Schiavoni, S.; Horoshenkov, K.V. A Review of Sustainable Materials for Acoustic Applications. *Build. Acoust.* **2012**, *19*, 283–312. [\[CrossRef\]](#)
14. Iannace, G.; Trematerra, A.; Trematerra, P. Acoustic correction using green material in classrooms located in historical buildings. *Acoust. Aust.* **2013**, *41*, 213–218.
15. Hasenstein, K.H.; Miklave, N.M. Hydroponics for plant cultivation in space—A white paper. *Life Sci. Space Res.* **2024**, *43*, 13–21. [\[CrossRef\]](#)

16. Ryu, J.H.; Baek, J.; Subah, Z. A low-cost autonomous and scalable hydroponics system for space farming. *HardwareX* **2025**, *21*, e00625. [[CrossRef](#)]
17. Asdrubali, F.; D'Alessandro, F.; Schiavoni, S. A review of unconventional sustainable building insulation materials. *Sustain. Mater. Technol.* **2015**, *4*, 1–17. [[CrossRef](#)]
18. Sánchez-Dehesa, J.; Garcia-Chocano, V.M.; Torrent, D.; Cervera, F.; Cabrera, S.; Simon, F. Noise control by sonic crystal barriers made of recycled materials. *J. Acoust. Soc. Am.* **2011**, *129*, 1173–1183. [[CrossRef](#)]
19. Ekici, B.; Kentli, A.; Küçük, H. Improving Sound Absorption Property of Polyurethane Foams by Adding Tea-Leaf Fibers. *Arch. Acoust.* **2012**, *37*, 515–520. [[CrossRef](#)]
20. Chidichimo, G.; Aloise, A.; Beneduci, A.; De Rango, A.; Pingitore, G.; Furgiele, F.; Valentino, P. Polyurethanes reinforced with Spartium Junceum fibers. *Polym. Compos.* **2015**, *37*, 3042–3049. [[CrossRef](#)]
21. Pöschl, M.; Vašina, M. Study of the Mechanical, Sound Absorption and Thermal Properties of Cellular Rubber Composites Filled with a Silica Nanofiller. *Materials* **2021**, *14*, 7450. [[CrossRef](#)]
22. Han, F.; Seiffert, G.; Zhao, Y.; Gibbs, B. Acoustic absorption behaviour of an open-celled aluminium foam. *J. Phys. D Appl. Phys.* **2003**, *36*, 294–302. [[CrossRef](#)]
23. ISO 10534-2; Acoustics-Determination of Sound Absorption Coefficient and Impedance in Impedance Tubes Part 2: Transfer-Function Method. ISO: Geneva, Switzerland, 1998.
24. ISO 9053-2; Acoustics—Determination of Airflow Resistance. Part 2: Alternating Airflow Method. ISO: Geneva, Switzerland, 2020.
25. Zulkifli, R.; Mohd Nor, M.J.; Ismail, A.R.; Nuawi, M.Z. Comparison of acoustic properties between coir fiber and oil palm fiber. *Eur. J. Sci. Res.* **2009**, *33*, 144–152.
26. Parikh, D.; Chen, Y.; Sun, L. Reducing Automotive Interior Noise with Natural Fiber Nonwoven Floor Covering Systems. *Text. Res. J.* **2006**, *76*, 813–820. [[CrossRef](#)]
27. Samsudin, E.M.; Ismail, L.H.; Kadir, A.A. A review on physical factors influencing absorption performance of fibrous sound absorption materials from natural fibres. *ARPJ. Eng. Appl. Sci.* **2016**, *11*, 3703–3711.
28. Allard, J.; Atalla, N. *Propagation of Sound in Porous Media: Modelling Sound Absorbing Materials*, 2nd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2009.
29. Katović, D.; Katović, A.; Antonović, A. Extraction Methods of Spanish Broom (*Spartium junceum* L.). *Drv. Ind.* **2011**, *62*, 255–261. [[CrossRef](#)]
30. Koruk, H.; Genc, G. Investigation of the acoustic properties of bio luffa fiber and composite materials. *Mater. Lett.* **2015**, *157*, 166–168. [[CrossRef](#)]
31. Kovacevic, Z.; Bischof, S.; Fan, M. The influence of *Spartium junceum* L. Fibres modified with montmorillonite nanoclay on the thermal properties of PLA biocomposites. *Compos. Part B Eng.* **2015**, *78*, 122–130. [[CrossRef](#)]
32. Chandramohan, D.; Marimuthu, K. Review on natural fibers. *Int. J. Recent Res. Appl. Stud.* **2011**, *8*, 194–206.
33. Lefebvre, J.; Genestie, B.; Leblanc, A. Cellulose-Based Acoustic Absorber with Macro-Controlled Properties. *Acoustics* **2024**, *6*, 1088–1099. [[CrossRef](#)]

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