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Reuse of coffee and tea waste for acoustical panel applications in architectural design studios

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ABSTRACT

This study has been initiated with the aim of enhancing acoustical comfort levels in architectural design studios. Initial assessment of the studios by field tests indicated very long reverberation times, supporting the complaints by the students and instructors. In order to be applied in a studio environment, acoustical panels are developed out of recycled materials. Increasing coffee demand and consumption of our era have motivated the reuse of coffee and tea waste. The end-product is composed of a panel of baked kiln-dried coffee grains and tea leaves. The coffee/tea residues are adhered together using natural binders. In order to determine the best possible alternative of the waste materials with the highest sound absorption performance, different variations are tested. Both impedance tube measurements and room acoustic simulations are utilized. Results indicate the potential improvement of the interior sound field of the studio environment by coffee-tea waste panel application. Considering the increasing demand for green technology, the layered panel system is proposing cost minimized, environmentally friendly and biodegradable solutions with improved acoustical and aesthetical values.

1. INTRODUCTION

The current world has surpassed the threshold of sustainability and moves towards an inevitable calamity through the use of non-environmentally friendly materials; in turn, the need for green technology increases rapidly every passing year. Therefore, increasing the use of sustainable, biodegradable, and environmentally friendly materials whenever possible becomes highly important. In the field of acoustics, traditional sound absorptive materials, which are used mostly in architectural applications, are generally mineral/stone/glass wool based materials. These materials add to the carbon footprint during their processing from raw material to the final product [1].

Coffee and tea are the two most popular beverages in the world. Global data indicates over 9.2 million tons of coffee and 6 million tons of tea consumptıon in 2017 alone [2]. This increases with the increase in human population, and the amount of derived waste leads to a huge environmental problem [3]. The waste of these beverages is quite commonly disposed to landfill areas, in which their natural decomposition takes a long time, and might cause further health issues for the surrounding locations [4,5]. The increasing demand and corresponding waste production have been the basic motivation behind this study.

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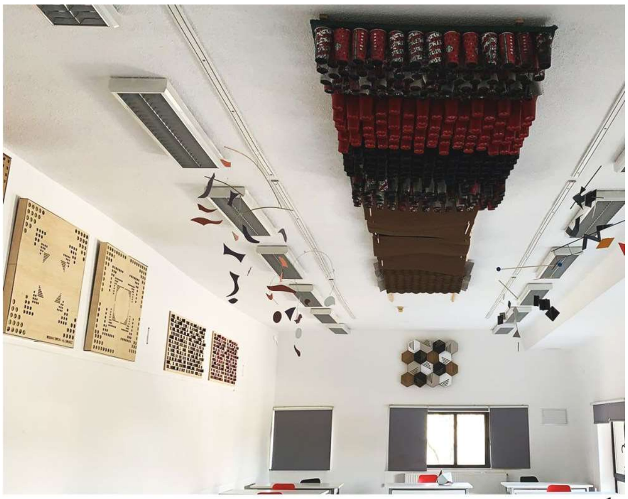
In an earlier study, Yun et al. investigated coffee waste and resin composition. The research focused on the sound absorption coefficient values of the coffee waste, and proposed to use them in coffee shops from where the material is collected, and where there is high reverberation time for a studying environment [6]. Additionally, different research groups have been investigating some other organic materials such as coconut husk and palm oil male flower spikes based on their sound absorption and reflection characteristics. In these cases, after testing the materials' qualities, researchers found that organic materials have promising potentials to be used in acoustical applications [7,8]. Thus, this study aims to further investigate the potential use of recycled coffee and tea residues in acoustical applications to increase sound absorption area; and later to apply single-use cardboard cups over exposed surfaces of the panels for further increasing the sound scattering.

This study initially originated as a term project for the course Architectural Lighting and Acoustics (ARCH 341) within the curriculum of the Department of Architecture in Bilkent University. Under the scope of this particular term project, students -in different groups- were required to enhance the acoustic comfort levels in their own architectural design studios by developing and producing acoustical panels. In Figure 1, the before and after the acoustical panel intervention conditions of the design studio FFZ08, which is chosen on the scope of the course, are shown.

Field measurements are held to further support the complaints by students and instructors within the problematic studio in accordance with ISO 3382 [9]. The results indicate that the reverberation time of the studio before panel application reaches up to 1.75 s in mid-frequencies and 2.09 s in low-frequencies. In order to control high reverberation times and improve the intelligibility of speech within the studio, originally a two-layered panel system was developed. In this initial phase, the first layer consisted of used cardboard cups collected from coffee shops to achieve the full recycled content. The collected cardboard cups differing in size were placed in different orientations, as shown in Figure 2. Additionally, the second layer was made of thick mineral wool providing structural stability while having an additional contribution to the system's absorption values. Nonetheless, in order to further develop the project in terms of the sustainability considerations mentioned above, biodegradable and recycled materials are investigated to replace the mineral wool. In turn, the aforementioned coffee and tea residues are chosen as the basis of the sound absorption material and transformed into coffee and tea panels (CTP) and coffee panels (CP). The production and the measurement methods are discussed in the following sections.

a



b

Figure 1: a) The studio before panel application, b) after the term project submission; students' panels applied to the design studio.

a b c d

Figure 2: Different panel arrangements, a) cut-in-half cardboard cups placed horizontally, b) cut-in-half cardboard cups placed vertically, c) cardboard cups having different sizes placed randomly, d) cardboard cups having different sizes arranged linearly in a pattern based on size.

2. METHODOLOGY

Two different methods are utilized during the research and development process: impedance tube testing and room acoustics simulation. The different alternatives of the composite coffee-tea waste samples are initially produced and tested by the impedance tube according to ISO 10534-2:1998 [10]. Later, the sample having the highest sound absorption coefficient between the frequency range of 250 Hz - 4000 Hz is determined, and applied in the simulations to compare the acoustical conditions before and after its application within the architectural design studio.

2.1. Sample Preparation

In order to reach the highest amount of recyclability and sustainability, the waste collection process can be considered as one of the most important steps of this study. Coffee and tea residues are obtained by drying domestic waste, and collecting waste from different coffee chains. Following the collection process, collected waste materials are laid out to the ground and left to air-dry at room temperature to reduce the moisture content (Figure 3a and 3b).

In order to bind grains/waste/particles to each other and make them gain enough structural stability, an organic binder is prepared. A starch-based organic material is selected as a binder with the intention of utilizing natural and biodegradable materials. This adhesive is prepared from flour, water, sugar, and vinegar to be combined with the dried coffee-tea residue mixture. The ingredients are mixed together on a stove for around five minutes. Afterwards, the ingredients become dense enough to bind the waste materials (Figure 3c).

a b c

Figure 3: Waste is dried separately at room temperature to minimize their moisture content, a) domestic tea residues, b) domestic coffee residues, c) photograph of the sample preparation: a mixture of the coffee and tea residues together with the natural binder.

To investigate the best possible variation, three types of samples are prepared. As the impedance tube is a cylinder (in two different diameters), circular-shaped samples having the diameter of 100 mm and 28 mm are prepared for each of the three samples with a thickness of 20 mm. These three samples have different compositions in terms of ingredients, and also they are baked in an oven for different durations in order to investigate the effect of baking. Sample A and Sample B are composed of dried coffee grains and tea leaves. At first, the dried composite is mixed with the starch-based adhesive, equaling approximately ⅓ volume of the whole composite, with the only difference between Sample A and Sample B being the baking time. While Sample A (Figure 4a) is baked for 1 hour, Sample B (Figure 4b) is baked for 2 hours at 200°C. Sample C (Figure 4c) is composed only of coffee waste and organic binder as ingredients to experiment with the acoustical absorption quality of solely coffee grains, without tea leaves. The sample is composed of 50% coffee waste, 50% organic binder. This sample is not baked but rather left to air-dry at room temperature.

a b c

Figure 4: Photographs of samples, a) Sample A (CTP), b) Sample B (CTP), c) Sample C (CP).

2.2. Impedance Tube Measurements

Measurements are performed with S.C.S. Kundt Tube. 'Kundt Tube' configuration represents the basic, standard system set up for absorption coefficient and acoustic impedance measurements (2 microphones - transfer function method), according to ISO 10534-2:1998 [9,10]. The double tube set-up of sound absorption measurements includes small and large tubes. Both tube types are utilized for CTP and CP tests in this study. The large one is made up of Ø100 mm tubes for measurements in the low-frequency range (50 Hz to 1200 Hz), while the small one is made up of Ø28 mm for measurements in the high-frequency range (1200 Hz to 8000 Hz). All samples placed in the tube were 20 mm thick, and backed up with a 30 mm air gap. In Figure 5, photographs of the impedance tube set-up and the placement of Sample A in the tube (Figure 5b) are provided. Each composition is measured several times for checking repeatability, and the average values of these multiple trials are utilized in the results of this study, excluding deviating data.

a b c

Figure 5: During the measurement of proposed products, a) the set-up, b) CTP Sample A, c) while the samples are being molded.

2.3. Room Acoustics Simulation

The aim of the room acoustics simulations is to test the relative enhancement that can be achieved as a result of the application of the proposed CTP Sample B, which is the alternative that resulted with the most desirable outcome. The results will be discussed in a more detailed way in the Section 3. The test is done by comparing the values of the studio before and after the panel intervention instead of obtaining the absolute acoustic parameter results of the room impulses. In this process, a simplified 3D graphical model of the existing studio is initially developed to use with ODEON Room Acoustics Software version 16.01. The absorption coefficients of the materials used in the simulation are presented in Table 1. The student capacity for the studio is approximately 16, and it has an estimated acoustic volume of approximately 526 m^3.

The study focuses on T30 values at 125, 250, 500, 1000, 2000 and 4000 Hz, SPL (A) (A-weighted sound pressure level), and speech transmission index (STI) results. In the distribution map results, the source is positioned 1.50 m off the floor (representing a speaking instructor), and the distance between receivers is set to be 0.4 m. In the analysis of speech intelligibility in the proposed scenario, the background noise level is assumed not to exceed the (NC30) level. Considering the fact that the panels perform not only as absorbers but also as scatterers to some extent, a scattering coefficient value of 0.3 is assigned within the simulation for the proposed panels. As shown in Figure 7c, the ray tracing simulation implies the area is fully enclosed, and there is no sound leak from inside to outside.

Simulations are initially run for the condition before panel application to the studio, and then for the scenario in which the proposed CTP sample B is applied to the ceiling for acoustical improvement. The dimensions of the ceiling are 15.5 m by 7 m, and the 3D view of the before panel application condition can be seen through Figure 6a and Figure 7a. Half of the ceiling is covered with the panels in the simulation, placed in a checkerboard pattern. The dimensions of each panel are 1.2 m by 0.6 m, covering a total area of 53.25 m^2. As shown through the OpenGL views in Figure 6, the reflective surfaces are dominant in the room. Figure 6b represents the proposed panels which are located with a gap between them as a checkerboard pattern. The difference between the results of the simulations of the empty studios and the results of the field tests for T30 over tested receiver positions is around 0.03 s, which is smaller than 1 JND, showing that the tuning of the acoustical model is sufficiently accurate.

Table 1: The interior finish materials present in the studio environment and their corresponding absorption coefficients obtained in the simulations together with the absorption coefficient value of the proposed product are listed by 1/1 octave bands from 125 Hz to 4000 Hz frequencies.

Material Location	**Name**	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Wall surfaces	Paint and plaster on brick wall	0.06	0.06	0.10	0.10	0.10	0.10
Ceiling surfaces	Painted concrete	0.10	0.05	0.06	0.07	0.09	0.08
Floor surfaces	Concrete or terrazzo flooring	0.01	0.01	0.02	0.02	0.02	0.02
Drawing table	Wood boards on a profile	0.15	0.20	0.10	0.10	0.10	0.10
Windows	Ordinary window glass	0.35	0.25	0.18	0.12	0.07	0.04
Door	Wood, 1 layer, 20 mm	0.25	0.18	0.11	0.08	0.07	0.06
Proposed Panel[a,b]	CTP (Coffee-tea residue, starch based adhesive)	0.08	0.17	0.74	0.78	0.43	0.64

Note: [a] Sound absorption coefficient values are obtained from the impedance tube measurement results.
[b] The scattering coefficient value is defined as 0.3 for the proposed panel.

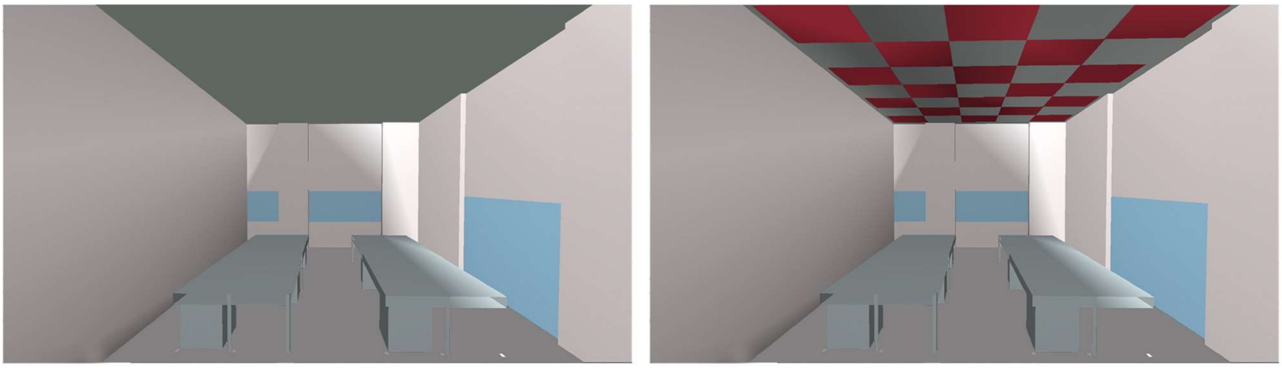
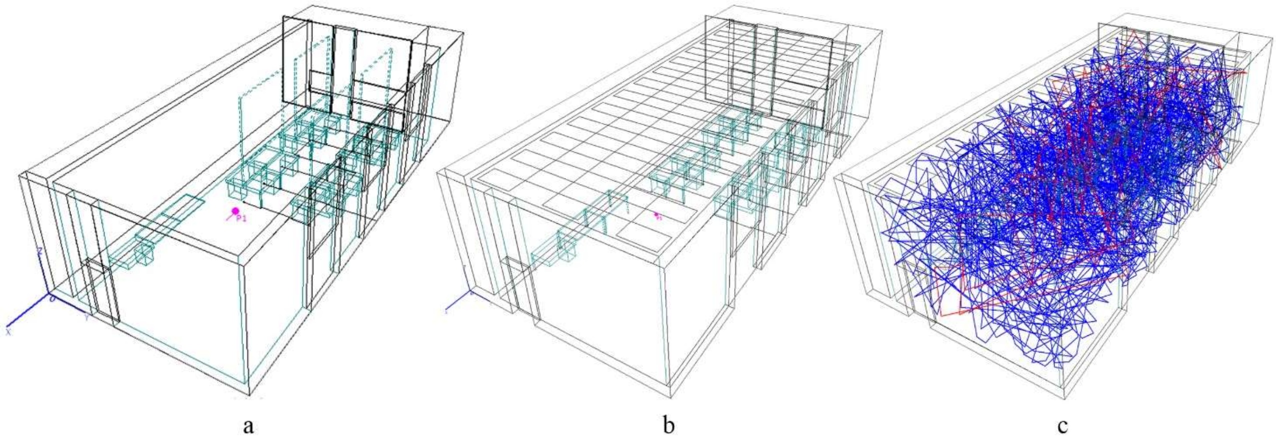


Figure 6: 3D OpenGL views, a) before panel application, b) after CTP Sample B panel application.



a b c

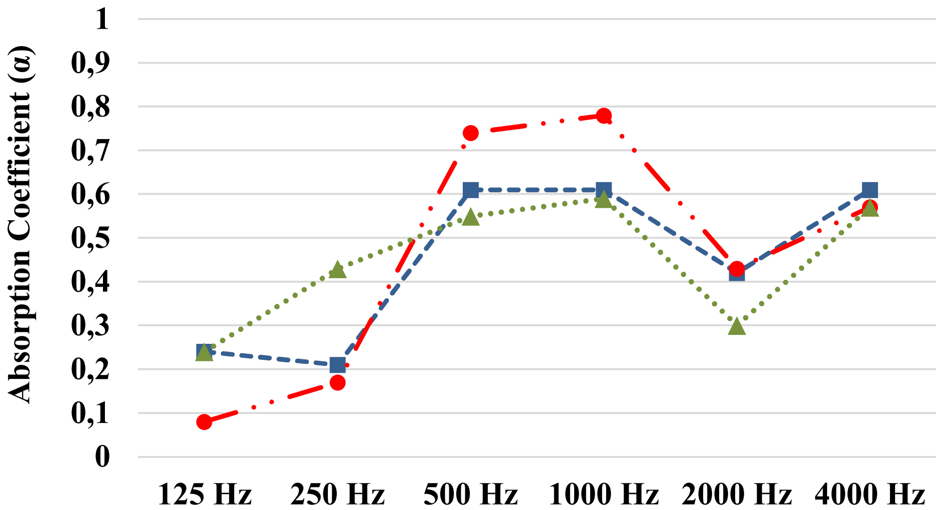
Figure 7: a) Before panel application, b) after CTP Sample B panel application, c) ray tracing acoustic simulation.

3. RESULTS

3.1. Impedance Tube Measurement Results

In this section, sound absorption coefficient measurement results of samples A, B, and C are presented. Figure 8 presents the average values of all the samples. When the results are examined, it can be stated that all three options have high sound absorption characteristics, especially over 250 Hz. Even the sound absorption coefficient values (i.e., alpha-α) at low frequencies (i.e., below 250 Hz) of these 20 mm thick samples, backed up with a 30 mm air gap, are much more absorptive in comparison to standard suspended ceiling panels. The alpha values vary between 0.21 and 0.61 in CTP Sample A; 0.08 and 0.78 in CTP Sample B; 0.24 and 0.59 in the CP Sample C between the octave bands of 125 Hz and 4000 Hz (Figure 8).

When results are compared for different samples, it can be seen that Sample B indicates the best overall result in terms of sound absorption values for octave bands in between 250 Hz and 4000 Hz, which is a convenient interval to consider while designing for a studio environment [11]. Even though Sample A might seem to have a better potential for low frequencies, the range is not as critical as high frequencies for the chosen environment. Therefore, Sample B, which is baked for 2 hours and has an equal combination of coffee & tea residues and organic binder, is utilized to carry out the room acoustics simulation.



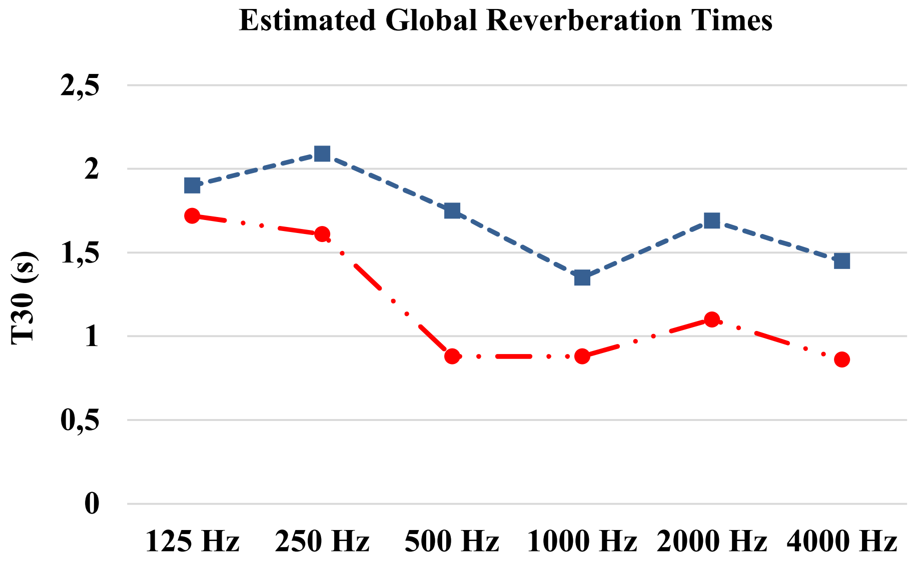
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Sample A [a]	0.24	0.21	0.61	0.61	0.42	0.61
Sample B [b]	0.08	0.17	0.74	0.78	0.43	0.57
Sample C [c]	0.24	0.43	0.55	0.59	0.30	0.57

Note : [a] CTP, baked for 1 hour; [b] CTP, baked for 2 hours; [c] CP, dried.

Figure 8: Sound absorption coefficient values over 1/1 octave bands (Hz) obtained from impedance tube test for the following configurations of the proposed products: CTP sample A, CTP sample B and CP sample C.

3.2. Simulation Results

Simulations are conducted with the chosen CTP Sample B, which possesses the highest absorption coefficient values over the largest frequency range (considering the speech frequencies) according to the results measured by the impedance tube testing. The studio where field tests were previously carried out (i.e., Bilkent University FFZ08 architectural design studio) is also chosen for the acoustical simulation, as explained in Section 2.4.



	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Before Panel Application	1.90	2.09	1.75	1.35	1.69	1.45
After Panel Application	1.72	1.61	0.88	0.88	1.10	0.86

Figure 9: Estimated global reverberation time for T30 over 1/1 octave bands, between 125 Hz and 4000 Hz frequencies.

Considering the fact that the optimum reverberation time for classrooms should be around 0.8 seconds for the given volume, it could be said that the application of CTP Sample B on the ceiling of the studio environment has allowed for the reverberation time to decrease to a more desirable level, especially in mid to high frequencies. Before panel application (Figure 6a and Figure 7a), the reverberation times were 2.09 s, 1.75 s, 1.35 s, 1.69 s, and 1.45 s for the frequencies of 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz respectively (Figure 9), which are far above the recommended limits for learning and studying environments [9]. When CTP Sample B is applied (Figure 6b and Figure 7b), the reverberation times for the same frequencies have decreased to 1.61 s, 0.88 s, 0.88 s, 1.10 s, and 0.86s, respectively (Figure 9). On average, a decrease of approximately 0.6 seconds in reverberation time for the aforementioned frequency (i.e., from 250 Hz to 4000 Hz) range can be seen. The best performance was achieved for 500 Hz by decreasing the reverberation time by 0.87 seconds from 1.75 s to 0.88 s. The selected CTP performed well for the frequency range between 250 Hz and 4000 Hz, and its performance can be improved in the low-frequency range by increasing the thickness of the material or increasing the air gap backing.

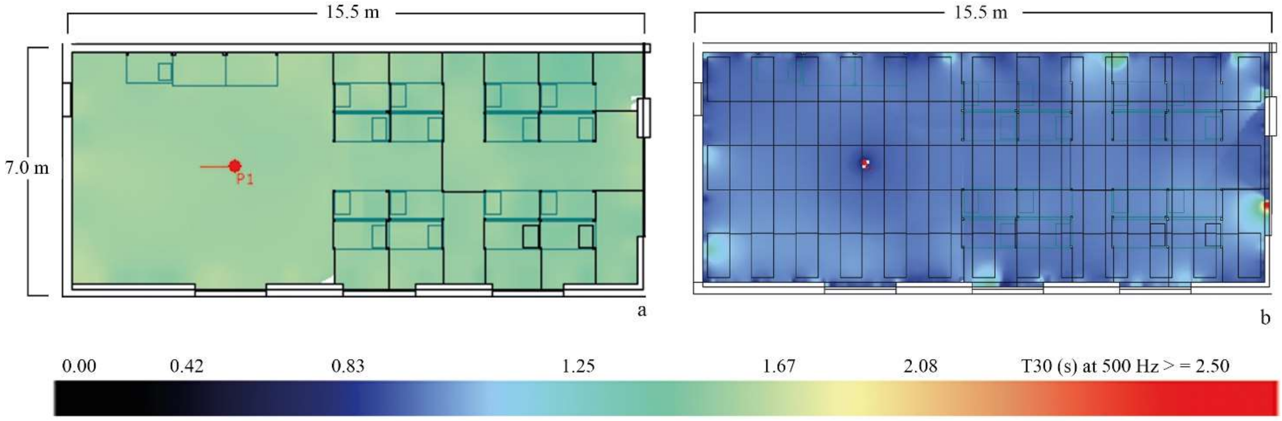


Figure 10: Distribution map of T30 (s) at 500 Hz, a) before panel application, b) after CTP sample B application.

The distribution map comparison before and after the acoustic panels for T30 (s) at 500 Hz is represented in Figure 10. The maps indicate that the distribution of the sound is even within the studio. Figure 11 shows the speech transmission index (STI) results for the studio before and after the proposed CTP intervention. In the studio scenario, an instructor is talking to the whole class from a central position. In the studio before panel application, the STI values indicate “fair” intelligibility in most of the receiver positions (Figure 11a). STI results of before acoustical panel application vary in the range of 0.47 and 0.56 whereas the results of CTP sample B application are between 0.57 and 0.68. At 50%, the STI values of composition before and after CTP sample B application are respectively 0.50 and 0.59 (Figure 11).

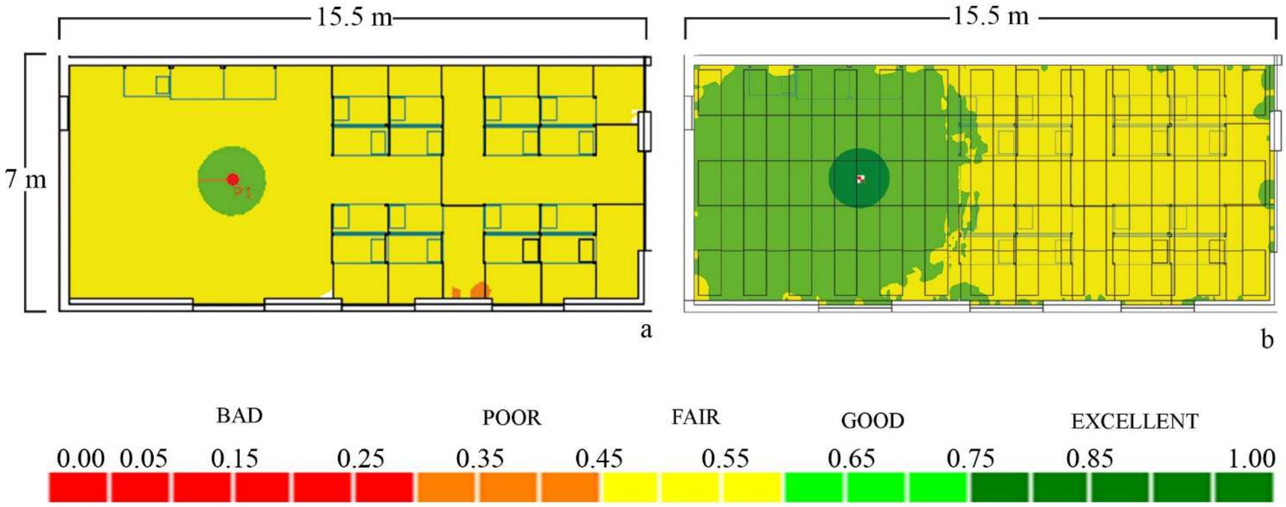


Figure 11: STI distribution map a) before panel application, b) after CTP sample B is applied.

The range of SPL (A) results before panel application is between 81.5 dB and 85 dB, while after CTP sample B is applied they differ in the range of 79 dB to 84 dB. At 50%, the SPL(A) before panel application is 83.3 dB, and after CTP sample B application, it is 81.2 dB. Therefore, there is a 2.1 dB difference at %50 between the two conditions (Figure 12).

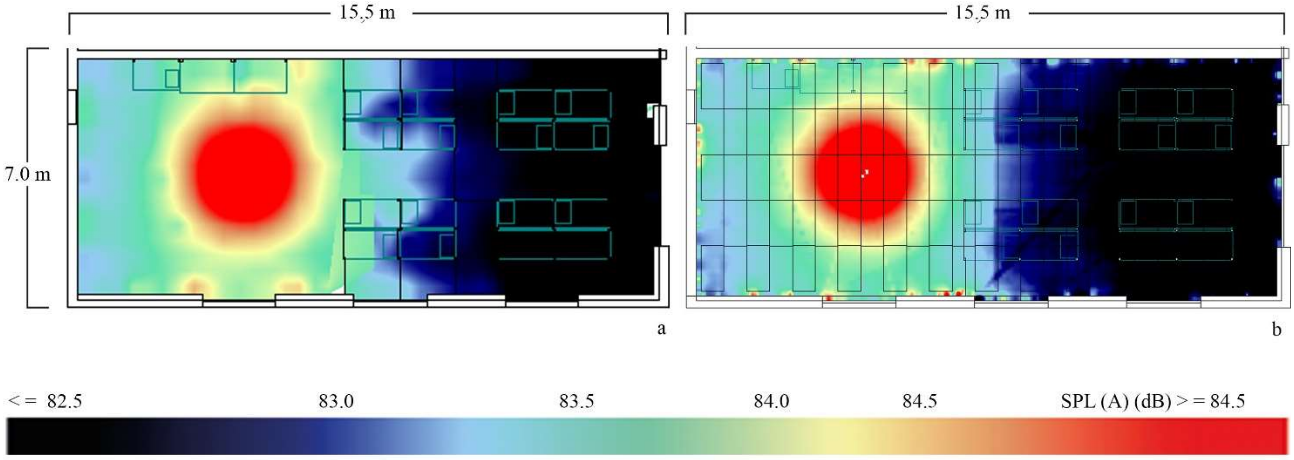


Figure 12: SPL (A) distribution map, a) before panel application, b) after CTP sample B application.

These results highlight the enhancements inside the studio and the potential benefits of the composite use of CTP with the coffee cups to solve a real architectural acoustics problem. Moreover, the proposed CTP applications do not use synthetic materials, and there is always an option to improve the aesthetic features of the space in question through the customization of the panels by utilizing a variety of coffee cups, which will be the further investigation of this study.

4. CONCLUSION

This study focuses on revealing the acoustic qualities of recycled and biodegradable materials as a potential solution for the high amount of waste produced by the increasing consumption of coffee and tea beverages globally. The current absorptive materials are generally based on inorganic materials and have comparatively high environmental impact since they are requiring a high level of energy to be produced and have an expensive process of production [2]. On the other side, this proposed CTP product serves as an alternative environmental solution by reducing the waste disposal to landfill areas and having an environmentally friendly, low cost and easy production process. Throughout the experimental process, three different composite samples' acoustical qualities have been tested to check their sound absorption performance. The impedance tube results are further utilized to simulate the studio environment with the developed panels. Simulation results highlight that the usage of coffee and tea waste in the production of acoustical panels has promising potential as a sound-absorbing material; and quite open for further investigation. Therefore, this study will continue by using recycled coffee cardboard cups with various patterns to increase the scattering as well as the absorption area of these surfaces. Following that, full-scale field tests will be held in a real application of CTP fronted with the coffee cups. The end product is aimed to be an aesthetically appealing green acoustical panel, which can be applied not only in architectural design studios but also in many other indoor spaces such as coffee shops.

5. ACKNOWLEDGEMENT

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6. REFERENCES

1. Buratti, C., Belloni, E., Lascaro, E. & Giovanna, L. Sustainable Panels with Recycled Materials for Building Applications: Environmental and Acoustic Characterization. *Energy Procedia*, **101**, 972–979 (2016).

2. Saldana-Mendoza, S. A., Ascacio-Valdes, J. A., Palacios-Ponce, A. S. *et al.* Use of wastes from the tea and coffee industries for the production of cellulases using fungi isolated from the Western Ghats of India. *Systems Microbiology and Biomanufacturing,* **1,** 33–41 (2021).

3. Van Hilten, H.J., Fisher, P. J. & Wheeler, M. A. *The Coffee exporter's guide: The Markets for Coffee,* 3rd Edition, International Trade Center, 2011.

4. Deloraine, A., Zmirou, D., Tillier, C., A., Boucharlat, A. & Bouti H. Case-Control Assessment of the Short-Term Health Effects of an Industrial Toxic Waste Landfill, *Environmental Research*, **68(2)**, 124–132 (1995).

5. Joseph, K., Rajendiran, S., Senthilnathan, R. *et al.* Integrated approach to solid waste management in Chennai: An Indian metro city. *Journal of Mater Cycles Waste Management* **14,** 75–84 (2012).

6. Yun, B., Cho, H., Kim, Y., Lee, S. & Kim, S. Circular reutilization of coffee waste for sound absorbing panels: A perspective on material recycling. *Environmental Research*, **184,** (2020).

7. Rimantho, D., Yulianti Hidayah, N., & Pane, E. Utilization of the organic and inorganic solid waste as acoustic material. *Journal of Engineering and Applied Sciences*, **14(8)**, 1502–1506 (2019).

8. Masrol, S. R., Rosdin, M. & Ibrahim, M. Sound absorption characteristics of palm oil male flower spikes fiber reinforced composite. (2013).

9. Yazıcı, B. & Gül, Z. Biomimetic metamaterial design simulation and evaluation for building acoustics by impedance measurements. *Journal of Testing and Evaluation,* **49**, (2021).

10. International Organization for Standardization, *Acoustics – Determination of Sound Absorption Coefficient and Impedance in Impedance Tubes – Part 2: Transfer- Function Method*, 1998.

11. Long, M. 17 - Design of Rooms for Speech, *Architectural Acoustics (Second Edition)*, pp. 637–671 (2014).