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Eco-Friendly and Biocompatible Material to Reduce Noise Pollution and Improve Acoustic Comfort in Healthcare Environments

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Abstract: Noise pollution negatively impacts people's mental and physiological health. Unfortunately, not only is noise present in hospital environments, but its level frequently exceeds recommended thresholds. The efficacy of passive acoustic absorbers in reducing indoor noise in these scenarios has been well-documented. Conversely, given their inorganic composition and their origin in the petrochemical industry, most of these materials present a risk to human health. Over the last few years, there has been a notable increase in research on eco-friendly, low-toxicity, and biocompatible materials. This work outlines a methodology for fabricating recycled acoustic panels from plastic bottles and PET felt composites. This study encompasses three key objectives: (i) a comprehensive biocompatibility assessment of the panels, (ii) an evaluation of their thermal and acoustic properties, and (iii) their applicability in several case studies to evaluate potential acoustic enhancements. Specifically, antifungal resistance tests, Volatile Organic Compound (VOC) emission assessment, and cell viability experiments were conducted successfully. Additionally, experimental procedures were performed to determine the thermal conductivity and thermal resistance of the proposed material, along with its sound absorption coefficients in diffuse field conditions. Finally, the potential benefits of using this biomaterial in healthcare environments to reduce noise and improve acoustic comfort were demonstrated.

Keywords: eco-friendly material; biocompatible material; noise reduction; building acoustics

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1. Introduction

Much research has shown that exposure to high levels of noise can have a range of negative consequences on the physical and mental health of human beings [1–3]. In a health environment, noise generated by biomedical equipment presents a risk of hearing loss for healthcare staff and discomfort for patients [4–8]. For instance, drills used in the dental industry emit a high-frequency noise ranging from 4.2 to 7.5 kHz produced by rotating components operating at speeds of 250,000 to 450,000 rpm and whose prolonged exposure has been shown to cause discomfort for patients and potential harm to dentists [9,10]. Another prevalent example is Magnetic Resonance Imaging (MRI), a non-invasive medical imaging technique that utilizes magnetic fields and radio waves to generate high-resolution images of internal body structures. The operational mechanism of MRI involves the use of gradient coils, which generate acoustic noise due to coil conductor vibrations caused by large Lorentz

forces. Empirical studies have shown that acoustic noise reduction plays a significant role in enhancing patient comfort during MRI procedures [11]. Overall, noise levels exceeding recommended thresholds are commonly observed in the health setting [12,13], and this elevated noise exposure may contribute to an increased risk of rehospitalization [14]. In this context, a significant number of researchers emphasize the critical importance of managing and mitigating noise pollution in hospital environments [12,13,15].

On the other hand, beyond their auditory or cognitive effects, noise is a biophysical phenomenon capable of influencing fundamental cellular processes [16–18]. Through the investigation of mechanotransduction and sonobiology, it has been observed that cells can detect and react to various mechanical stimuli, including audible acoustic waves [19]. In this regard, decades of research have shown that mechanotransduction processes play a critical role in the regulation of cellular homeostasis and play an important role in wound healing, bone health, and cancer [20–23]. However, most of these studies have been conducted under non-biocompatible conditions, as the predominant noise control materials utilized in the biomedical field are those used in the construction industry [16,24,25].

Sound-absorbing elements used in the construction industry for noise control are typically inorganic and synthetic panels made of porous materials derived from the petrochemical industry (e.g., rock wool, glass wool, polyurethane foam, or polyester fiber). The acoustic properties of these so-called building acoustics materials are highly dependent not only on their thickness and position but also on their composition, which determines the porous microstructure responsible for acoustic energy dissipation [26]. In this regard, some excellent references describe how the microstructure of porous media determines the viscothermal effects responsible for sound attenuation [27], how this media can be used to absorb sound indoors [28], or how to improve noise isolation when embedded in constructive solutions [29].

However, these materials have a significant environmental impact during their production processes [30,31]. Additionally, there are potential health effects in terms of toxicology associated with the use of these materials [32,33]. Growing awareness of the associated environmental implications and health issues has led to increased research on eco-friendly, low-toxicity, and biocompatible materials [31,34–37]. Experimental and numerical investigations with eco-friendly materials, such as polyurethane foam, hybrid natural insulating materials, or cork sheets, have reported positive results [38–40].

A comprehensive review of sustainable materials for acoustic applications can be found in [41]. In this review, the authors show that natural or recycled materials are quite often a valid alternative to traditional synthetic materials, their production having a lower environmental impact than conventional ones. Ever since, many researchers have proposed the use of these materials and developed prediction models [37,42] that were shown to be very useful as guidelines in the design stage of sound absorption solutions. In fact, the regulations resulting from the current environmental and energetic crisis have fostered the use of these sustainable materials in many engineering applications, especially in the building sector [43].

Nevertheless, it is crucial not only to carefully evaluate the acoustic properties of these materials but also to ensure they meet the criteria for biocompatibility, minimal particle release, and antifungal characteristics when developing strategies to reduce noise pollution in healthcare environments. The current global shift towards environmentally sustainable materials in response to climate change highlights the importance of developing eco-friendly solutions for reducing noise pollution. Recent research has shown that the use of materials derived from polyethylene terephthalate (PET) shows both a high acoustic and thermal performance [44].

This work outlines a methodology for assessment of the applicability of recycled acoustic panels made from plastic bottles and PET felt composites in healthcare environments. To this end, (i) a biocompatibility assessment of the panels, (ii) an evaluation of their thermal and acoustic properties, and (iii) the modeling of two case studies in healthcare environments were carried out, analyzing the potential improvements both in noise pollu-

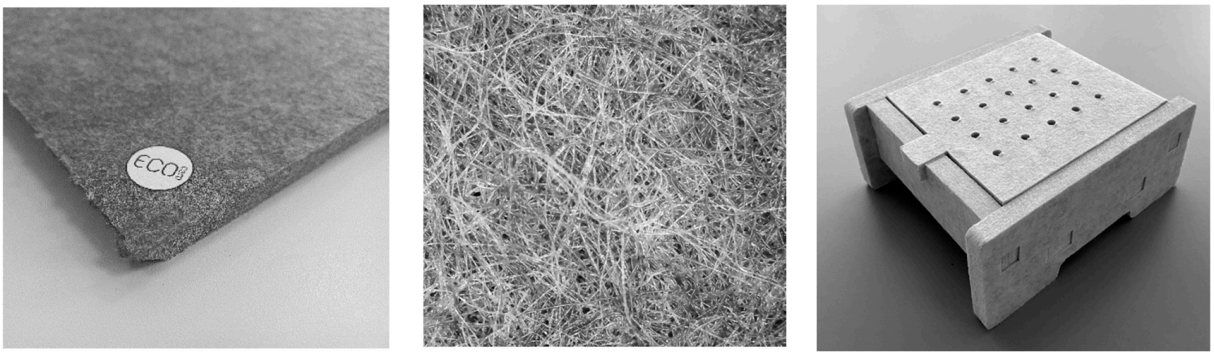
tion reduction and acoustic comfort. Specifically, an antifungal resistance test, a Volatile Organic Compound (VOC) emission test, and a cell viability experiment were performed. Next, experimental measurements were conducted following standardized procedures to determine thermal conductivity and thermal resistance along with the sound absorption coefficient of the proposed material in diffuse field conditions. Finally, the acoustic comfort improvements resulting from their practical application in two different healthcare scenarios are presented.

2. Materials and Methods

This section provides a comprehensive overview of the fabrication of biocompatible acoustic materials for the mitigation of noise pollution in health environments along with the methods used to evaluate their biocompatibility and to assess their sound absorption performance.

2.1. Eco-Friendly Acoustic Panels Made from PET

Recycled polyethylene terephthalate (PET) derived from industrial and domestic waste was used to prepare eco-friendly acoustic panels. After a process of cleaning the plastic bottles and then sorting them by color, they were compressed and crushed at a rate of 75 units per square meter, resulting in the production of PET flakes. The PET flakes then underwent a melting and extrusion process with a needle filament manufacturing machine to obtain a yarn of the desired thickness and density. Finally, a low-melting binder was mixed with the filaments and pressed with hot rollers to achieve a completely smooth surface. The final dimensions of the acoustic panels after a smooth cutting process were 2440 × 1220 mm, and their thicknesses were 8 mm, 12 mm, and 24 mm (see Figure 1a). The described production process ensured precision at every stage, from cutting to product finish, resulting in a CE-certified panel that meets European regulations both in terms of safety and performance. Besides, it should be noted that strict quality control is performed during the fabrication process to guarantee both the repeatability and uniformity of the prepared panels. Specifically, the automation fabrication process yields panels with a classification Euroclass B-s1, a d0 rating in fire safety, and GOLD classification both in LEED and BREEAM certifications, as well as GLOBAL RECYCLED STANDARD y OEKO-TEX STANDARD 100.



(**a**) (**b**) (**c**)

Figure 1. Eco-friendly acoustic panel: (**a**) rectangular sample of the fabricated material; (**b**) image taken with SEM for inspection of the fibrous microstructure; and (**c**) picture of the rectangular-shaped box designed for the cell viability assay.

Upon completion of the procedure, it was verified that the material conforms to SCS Recycled Content Standard V7-0 for a Minimum of 60% Post-Consumer Recycled Polyester [45]. Several samples were produced to perform the characterization tests to be described next. SEM images of the microstructure of the resulting fibrous samples are depicted in Figure 1b. The biocompatibility study was conducted in a rectangular-shaped

box of the produced material designed with dimensions of 148 × 124 × 85.5 mm^3, and the panel used was 12 mm thick. The resulting box where the biological samples were introduced had evenly distributed perforations 6.89 mm in diameter both in the lid and in the base to ensure inside-outside gas equilibrium (see Figure 1c).

2.2. Biocompatibility Assessment

2.2.1. Antifungal Resistance

The ASTM G21-15 protocol is a widely accepted procedure for evaluating the antifungal properties of synthetic polymer materials [46]. Synthetic polymers exhibit resistance to fungal growth due to their lack of carbon availability for fungi. Fungal growth is typically sustained by plasticizers, cellulosic components, lubricants, stabilizers, or added colorants in the polymer material. In practical applications, the ASTM G21-15 method involves inoculating test samples with a spore-rich suspension containing five specific organisms: *Aspergillus brasiliensis* (ATCC 9642), *Talaromyces pinophilus* (ATCC 11797), *Chaetomium globosum* (ATCC 6205), *Trichoderma virens* (ATCC 9645), and *Aureobasidium pullulans* (ATCC 15233). The test specimens subjected to a concentration of 106 spores/mL and a viability control were incubated at a temperature of 28 to 30 °C (FormaTM Steri-CycleTM CO_2 incubator model 371, Thermo Electron Corporation, Waltham, MA, USA) and a relative humidity of at least 85% for 28 days. Following the incubation period, the samples were analyzed using a microscope with a magnification of 10X (Nikon Eclipse TE200).

2.2.2. Volatile Organic Compounds (VOC) Emission

The standard environmental chamber test methods are common certification procedures, and they have been widely studied [47,48]. A custom-made test chamber of stainless steel was used to determine the VOC emission rate of the studied material. Before loading the chamber, a multi-step air purification process is conducted, followed by a blank check of the empty chamber. The operational parameters are detailed in Table 1.

Table 1. Parameters of the test methodology used for Volatile Organic Compound (VOC) testing.

Parameter	Value	Parameter	Value
Chamber volume	119 L	Relative humidity of supply air	50 ± 3%
Air Change rate	0.5 h^{-1}	Temperature of supply air	23 ± 1 °C
Area-specific ventilation rate	0.5 m/h	Loading factor	1 m^2/m^3

The emissions of VOC were assessed by extracting sample air from the outlet of the test chamber through Tenax® TA tubes after 3 and 28 days of storage in the ventilated test chamber. The analysis was performed by ATD-GC/MS with an HP-5 column (30 m, 0.25 mm internal diameter, 0.25 µm film thickness) following EN 16516 and ISO 16000-6 [49,50]. Likewise, the emission of carcinogens classified as European law Categories C1A and C1B were assessed by sampling air from the outlet of the test chamber using Tenax TA tubes after the specified period. Quantification was achieved using the total ion chromatogram (TIC) signal and authentic response factors. The presence of aldehydes and phthalates was tested by drawing air samples from the test chamber outlet through DNPH-coated silica gel tubes and with XAD-II adsorbent after the specified duration, respectively. For aldehydes, analysis was performed by solvent desorption followed by HPLC and UV-/diode array detection. The identity was finally checked by comparing full scan sample UV spectra. For phthalates, analysis was performed by solvent desorption and subsequently by GC/MS. Regarding the scope of the test, only substances capable of adsorption on Tenax TA and following thermal desorption were within the range of detection. Any emissions of substances that do not adhere to these specific criteria may not be reliably detected.

2.2.3. Cell Viability

In addition to antifungal properties and low VOC emission, a biocompatible material must also guarantee adequate cell dynamics. The 661W cell line was employed in the study of viability. This cell line, originating from a transgenic murine retina, exhibits the expression of photoreceptor markers and retinal ganglion cell markers [51,52]. The cells were seeded at a density of 100,000 cells per flask and incubated at 37 °C with 5% CO_2 in Dulbecco's Modified Eagle's Medium (DMEM) containing 4.5 g/L glucose and supplemented with 2 mM L-Glutamine, penicillin/streptomycin, and 10% (v/v) heat-inactivated fetal bovine serum (all reagents were procured from Capricorn Scientific GmbH, Ebsdorfergrund, Germany). Images of the 661W cell line were captured using an optical microscope (Nikon Eclipse TE200, ×10) after 24 h of incubation (i) for the culture plate in the CO_2 incubator (control condition) and (ii) for the culture plate within a sample (see Figure 1c) constructed from the material under study (sample condition). Cell morphology, adhesion, and confluence were examined for abnormalities.

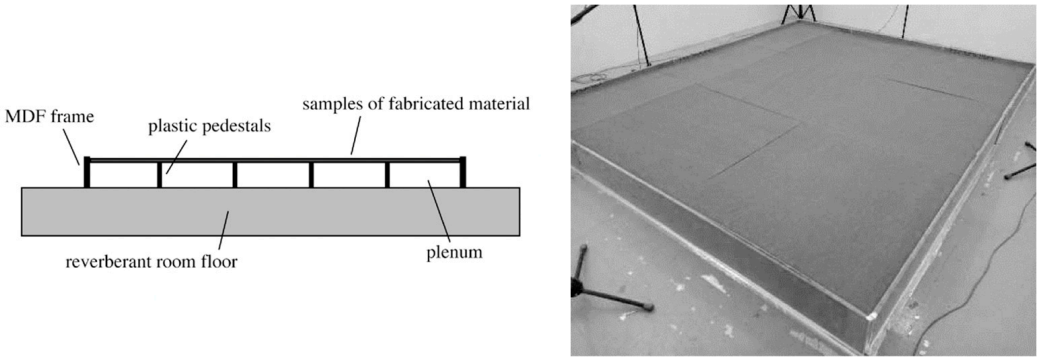
2.3. Thermal Conductivity and Thermal Resistance Tests

Thermal analysis is a common test for material research [39]. Before testing, the samples were conditioned in a chamber to achieve constant mass at (23 ± 2) °C and (50 ± 5)% relative humidity. The following successive weightings were performed at 24-h intervals until a constant weight was reached. Tests based on Standard EN 12667:2001 were conducted to measure thermal conductivity using a guarded hot plate [53]. The samples, with symmetrical dimensions of 500 × 500 mm and a measurement area of 150 × 150 mm, were tested using the Lambda-Meter EP 500, designed to minimize edge heat losses. The environmental conditions surrounding the equipment were maintained at (23 ± 5) °C. During testing, the samples were positioned horizontally with a descending flow, and the hot side of the samples was placed on the upper side. The temperature difference applied was 15 K, with an average ambient temperature of 10 °C. Drying was not performed in the heater conditioning. The density of the samples was 168.9 kg/m^3.

2.4. Sound Absorption Performance Assessment

Sound absorption tests were carried out to determine the sound absorption coefficient of the material in diffuse field conditions by performing experiments in a reverberant chamber. This test was conducted following the UNE-EN ISO 354:2003 standard, while the evaluation of the results was carried out following the ISO 11654 standard [54]. A spectrum analyzer (Bruel&Kjaer mod. Pulse LAN-XI), a diffuse field microphone (Bruel&Kjaer mod. 4943), an omnidirectional source (AVM mod. DO12), a noise generator (Bruel&Kjaer model 1049), and a power amplifier (INTER model M700) were used for the experiments. White noise was used to excite the sound source. As for the reverberant chamber, it had a dimension of 7835 × 4956 × 6271 m^3 (total volume of 243.5 m^3 and total surface area of 238.1 m^2) and 14 diffusers, and the tests were performed at a temperature of 20.2 °C with a humidity of 44.2% and an atmospheric pressure of 1008.1 hPa.

The tested material had a total surface area of 10.85 m^2 (3005 × 3610 mm^2) and consisted of six panels of 1200 × 1200 mm^2 and three panels of 600 × 1200 mm^2, with nominal thicknesses of 9 mm, 12 mm, and 24 mm for each experiment, arranged side by side without any gap between them. Measurements were performed for typical configurations in building acoustics applications: without plenum (i.e., rigidly backed samples) and with plenum (i.e., air-cavity-backed samples). This latter configuration can be easily achieved by sealing the lateral perimeter of the samples with a supporting frame and using plastic pedestals. In the current tests, an MDF frame (250 mm in height and 19 mm in thickness) with a rectangular cross-section of 65 × 16 mm^2 was glued to the floor of the reverberant chamber with adhesive tape (see Figure 2). Therefore, the configurations tested included assays without a backing air cavity and with a 200 mm backing air cavity. These tested configurations served to assess the sound absorption performance of the material under diffuse field conditions when used in typical arrangements of building acoustics.



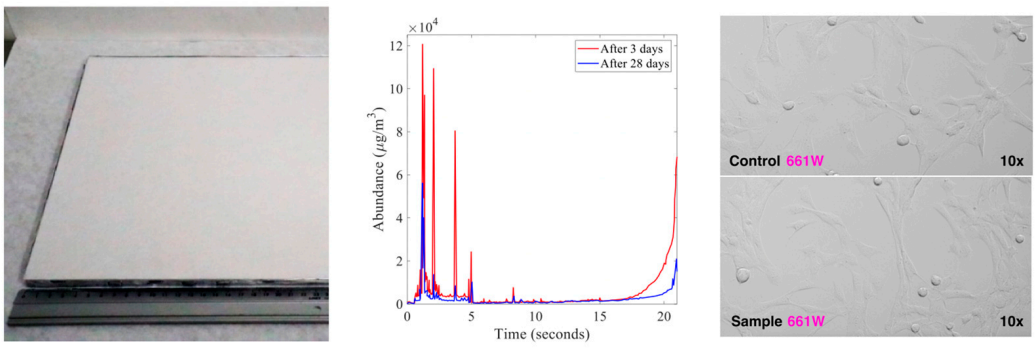
(**a**) (**b**)

Figure 2. Sound absorption tests of the material under study: (**a**) schematic representation of the setup used for measurements with the plenum following ISO 10534-2; and (**b**) detailed view of the samples arranged for the tests in the reverberant chamber.

3. Results

3.1. Biocompatibility Assays

First, the antifungal properties of the synthetic polymeric material under study were analyzed to evaluate biocompatibility. The experiment was conducted following the ASTM G21-15 (2021) guidelines outlined in Section 2.2.1. The absence of fungi was confirmed following a 28-day incubation period, as depicted in the sample in Figure 3a. Concerning the analysis of VOCs, after a 28-day exposure period in the experimental chamber, the following compounds were obtained: TVOC, toluene, tetrachloroethylene, ethylbenzene, xylene, styrene, 2-butoxyethanol, 1,2,4-trimethylbenzene, and 1,4-dichlorobenzene, exhibiting a reduced concentration of 2 $\mu g/m^3$. Concurrently, the concentrations of formaldehyde and acetaldehyde compounds decreased to 3 $\mu g/m^3$ (see Figure 3b). The material under study presents low VOC emissions, following French VOC, French CMR, Italian CAM Edilizia, ABG/AgBB, Belgian Regulation, Indoor Air Comfort®, Indoor Air Comfort GOLD®, BREEAM® International, BREEAM® NOR, and LEED v4.1 BETA protocols or regulations. The last biocompatibility test was a cell dynamic viability study. Cells of the 661W line were seeded in a culture plate and incubated for 24 h inside and outside an acoustic sample. They were then photographed and examined under the microscope for any abnormalities. Cell morphology and adhesion were normal (see Figure 3c).



(**a**) (**b**) (**c**)

Figure 3. Results of the biocompatibility tests: (**a**) sample of material with no specimens identified after antifungal resistance test; (**b**) chromatography of the VOC emission test after 3 days (red line) and after 28 days (blue line); and (**c**) optical microscopy images (10×) of the 661W cell line seeded at a density of 100,000 cells per flask of the 661W line in (Top) control and (Bottom) sample conditions.

3.2. Thermal Conductivity and Thermal Resistance Results

Under controlled environmental conditions (21.2 °C and 44% relative humidity) with an uncertainty of ±0.002 W/m·K, the thermal conductivity of the material under study was measured (see Table 2). The sample, with a thickness of 25 mm, exhibited a flow heat density of 24.174 W/m^2, a thermal resistance of 0.621 m^2·K/W, and a thermal conductivity of 0.040 W/m·K when subjected to a temperature difference of 15 K and an average test temperature of 10 °C. The conditioned mass change was zero. During testing, no variation in thickness was observed, and the change in mass during the test was recorded as 0.0004. Additionally, thermal resistance values for various sample thicknesses were calculated, yielding 0.225 m^2·K/W for 9 mm, 0.300 m^2·K/W for 12 mm, and 0.600 m^2·K/W for 24 mm, respectively.

Table 2. Thermal properties of the sample with 25 mm thickness.

Parameter	Value	Parameter	Value
Temperature difference	15 K	Average temperature during test	10 °C
Sample thickness	25 mm	Flow heat density	24.17 W/m^2
Thermal resistance	0.62 m^2·K/W	Thermal conductivity	0.04 W/m·K

3.3. Sound Absorption Results

To evaluate the sound absorption performance of the material under study, the sound absorption coefficient was measured in a reverberant chamber (diffuse field conditions). Figure 4 shows the resulting sound absorption coefficient data.

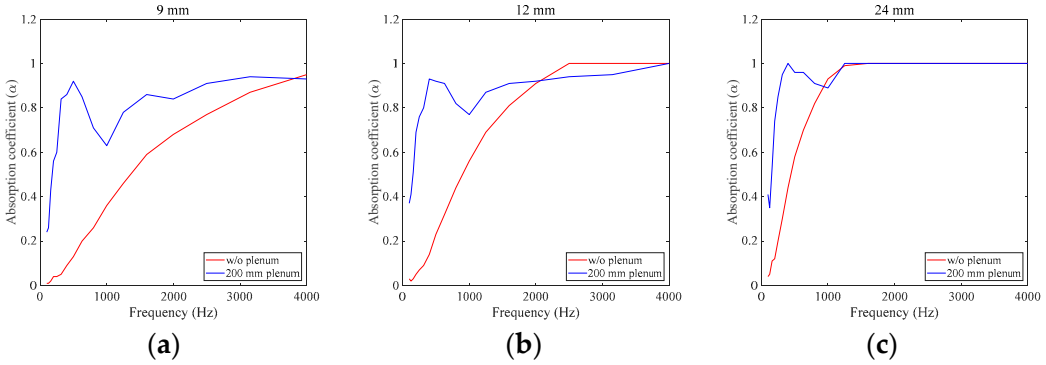


Figure 4. Sound absorption coefficient data obtained following the standardized procedure ISO 354 (reverberant chamber) for different thicknesses: (**a**) 9 mm, (**b**) 12 mm, and (**c**) 24 mm. Note that the tests were performed under two different conditions: without a plenum (red line) and with a 200 mm plenum (blue line). The weighted sound absorption coefficients (UNE-EN ISO 11654:1998) were 0.25 (0.8), 0.3 (0.9), and 0.5 (0.95), respectively; the values in parentheses correspond to the plenum arrangement.

In general, the sound absorption tests indicated that the material under study shows a good absorption performance in diffuse field conditions, especially for the plenum configurations. As expected, a shift towards low frequencies can be observed as the thickness of the panel or the plenum size increases, thus allowing for improved absorption in the low and mid frequencies. The weighted sound absorption coefficients calculated according to the UNE-EN ISO 11654:1998 were 0.25 (0.8) for the 9 mm panel, 0.3 (0.9) for the 12 mm panel, and 0.5 (0.95) for the 24 mm panel; the values in parentheses correspond to the plenum arrangement, and their acoustic absorption classes were E (B), D (A), and D (A), respectively. Therefore, the results presented so far indicate that the proposed material not only shows a good sound absorption performance at medium and high frequencies but also meets the requirements necessary for its use in healthcare environments. For this

reason, it was found of great interest to analyze its application in a case study, as will be described next.

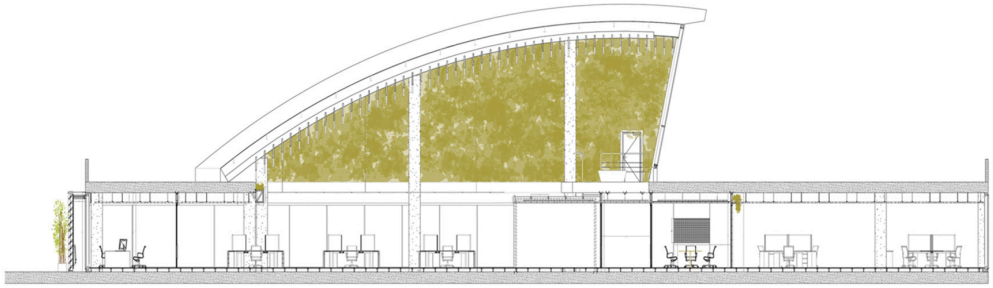
3.4. Case Studies for Noise Pollution Reduction and Acoustic Comfort Improvement in Healthcare Environments

To assess the potential applicability of the material under study in healthcare environments, the adoption of an acoustic treatment in two realistic scenarios was simulated using a modeling tool. These scenarios consisted of an office building and a childcare room. The acoustic simulations were performed using EASE (Enhanced Acoustic Simulator for Engineers) version 4.3 to evaluate the acoustic performance of the material under study both in terms of noise reduction and acoustic comfort. This software uses an advanced prediction scheme that relies on the ray tracing theory, the image-source method, and Statistical Energy Analysis [SEA] to calculate the Reverberation Time (RT); the intelligibility parameters Speech Clarity (C50), Speech Transmission Index (STI), and %Alcons (percentage Articulation Loss of Consonants) were calculated for both scenarios before and after the acoustic treatment. The simulation domain was discretized using a grid size of 1 cm to allow a detailed resolution of the acoustic phenomena within the simulated spaces. The sound absorption data at different frequencies used in the simulations for the materials of the walls, ceiling, and floor of the room (e.g., concrete, wood, glass) were retrieved from several relevant references [55–58]. In contrast, for the proposed material, the data presented in Section 3.3 were used. The number of rays and reflections considered were set to a minimum of 120,000 rays and a split time of 50 ms, thus guaranteeing enough accuracy and an affordable calculation time; the calculated octave bands were chosen in the frequency range necessary to assess speech intelligibility.

3.4.1. Case Study I: Office Building

The first case study consisted of a building having a surface area of 1482 m^2 with a parabolic oscillating height of between 3.5 and 11 m distributed over a single floor. Although these are the central facilities of a real textile company located in Málaga (Spain), the forthcoming study can be extended to the administrative areas of a healthcare building. Figure 5a,b show a plan view and rendered view of the building obtained using AutoCAD 2024 and Autodesk 3ds Max 2024, respectively. To acoustically characterize the useful space, RT measurements were carried out in situ beforehand at several representative points according to the ISO 3382-1 and ASTM E2235 standards (see Figure 5c–e) [59,60]. The measuring equipment consisted of a RION NA-28 sound level meter, and a balloon burst was used as an acoustic source. The measurements were taken at a temperature of 21 °C and a humidity of 55%.

Once the experimental characterization was finished, simulations were performed for the empty space, and the calculated RT was compared to the experiments, showing a good agreement in the frequency range of analysis (see Figure 6a). In brief, the simulations predicted an average RT of 7.08 s in the bands of interest (500, 1000, and 2000 Hz), with standard deviations of $\pm$1.294, $\pm$0.000, and $\pm$1.216 when compared to the RT measured in situ. As for the C50, STI, and %Alcons values in the areas most frequented by the alleged patients and healthcare workers, these were $-$12 dB, 0.27, and 39.12%, respectively, thus showing the poor intelligibility of the empty space and encouraging the need for an acoustic treatment.



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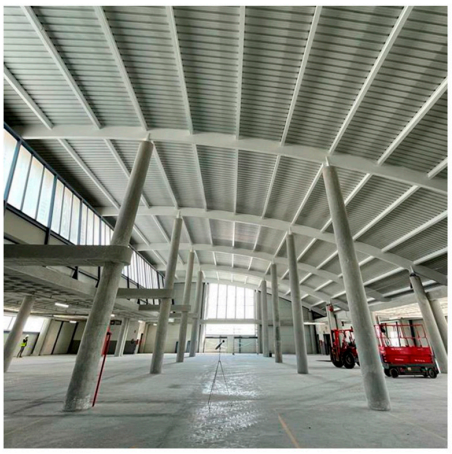

(**c**)

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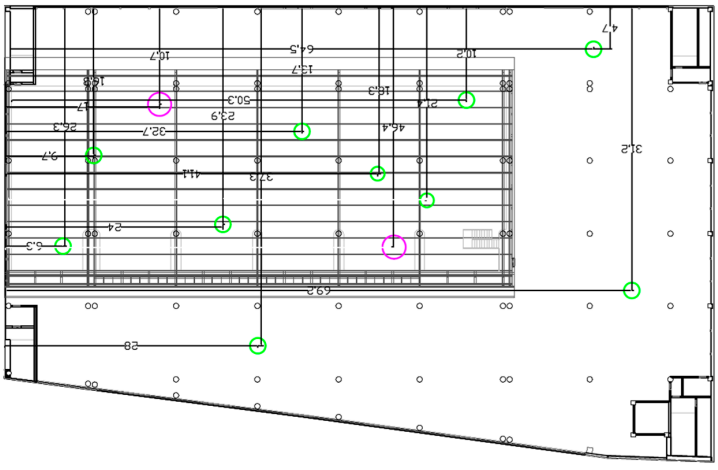

(**e**)

Figure 5. Case Study I, office building: (**a**) plan view; (**b**) rendered view; (**c,d**) pictures of the in situ RT measurements according to the ISO 3382 and ASTM E2235 standards; (**e**) plan view indicating source (pink circles) and microphone (green circles) positions.

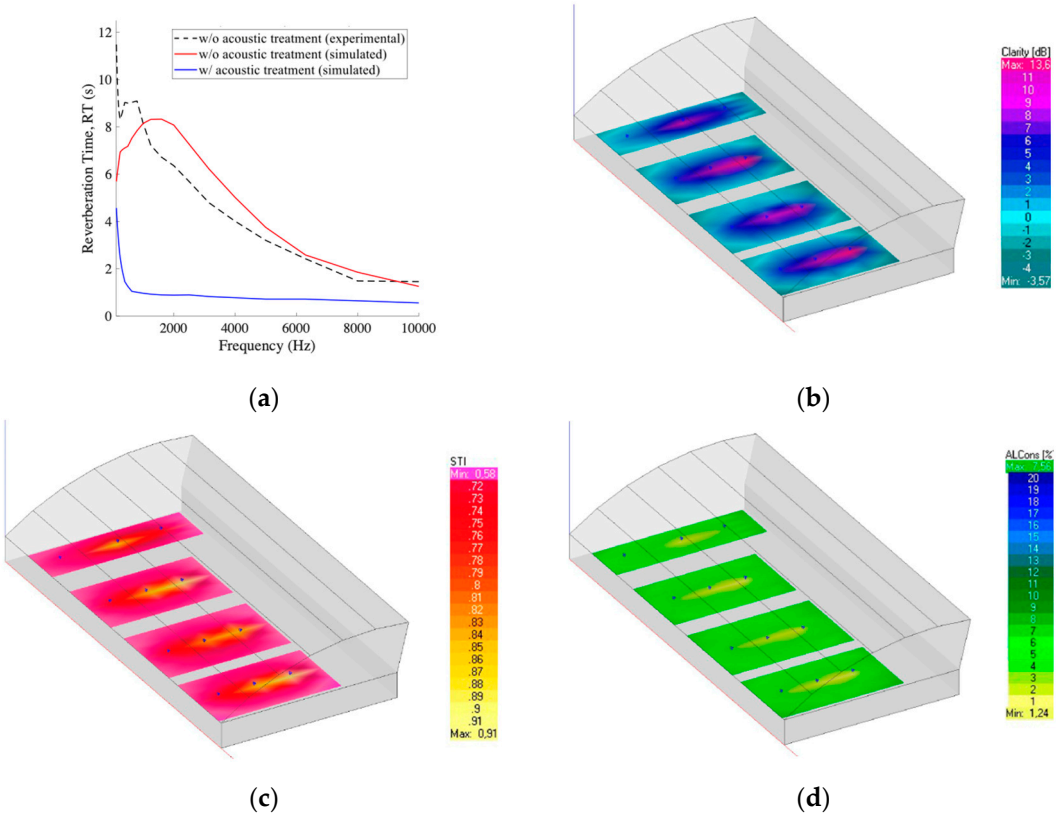

Figure 6. Noise pollution reduction and improvement of acoustic comfort in Case Study I: (**a**) comparison of the experimental (discontinuous black line) and predicted RT for the configurations without acoustic treatment (continuous red line) and with acoustic treatment (continuous blue line); (**b**) C50; (**c**) STI; and (**d**) %Alcons distribution over the useful space (areas most frequented by the alleged patients and healthcare workers).

Next, simulations including acoustic treatment with the biocompatible material were performed. Specifically, 95% of the ceiling area was covered with the biocompatible material. On the side walls, an equivalent area was covered with additional panels assembled without a plenum. Based on the environmental parameters, geometry, and materials that make up the room, RT, C50, and STI %Alcons values were calculated. Figure 6a shows that the simulated model predicted an RT reduction of 5.87 s at 500 Hz, 7.2 s at 2000 Hz, and 4.25 s at 4000 Hz. Consequently, following the inclusion of the acoustic material under study in the model, the average RT in the main room after acoustic treatment was 1.03 s. The material performance thus confirmed the laboratory sound absorption tests and significantly reduced the reverberant field. Likewise, the C50 was increased up to 10.65 dB, the STI intelligibility factor improved up to 0.57, and the %Alcons was reduced to 31.56%. Figure 6b,c show the C50 and STI values in the areas most frequented by the alleged patients and healthcare workers. Table 3 presents the average values of Reverberation Time (RT), Clarity Index (C50), Speech Transmission Index (STI), and Articulation Loss of Consonants (%Alcons) for Case Study I, both without and with acoustic treatment.

Table 3. Improvements in terms of acoustic comfort achieved in the assumed healthcare environment for Case Study I.

Parameter	Without Acoustic Treatment	With Acoustic Treatment
RT (s)	7.08	1.03
C50 (dB)	−12	−1.35
STI	0.27	0.58
%Alcons (%)	39.12	7.56

The environment without acoustic treatment had poor acoustic performance, with an RT of 7.08 s, a C50 of −12 dB, an STI of 0.27, and a %Alcons of 39.12%, all classified as "bad" according to the objective rating of speech intelligibility by the speech transmission index [61]. Upon applying acoustic treatment, significant improvements were observed: RT was reduced to 1.03 s, C50 increased to −1.35 dB, STI improved to 0.58, and %Alcons decreased to 7.56%, classified as "acceptable", "good", and "acceptable", respectively. These results indicated that the acoustic treatment effectively enhanced the auditory conditions of the assumed healthcare environment for Case Study I.

3.4.2. Case Study II: Childcare Room

The second case study consisted of a playroom of the Pediatric Oncology Department of the la Paz University Hospital (Madrid, Spain), having a surface area of 15 m^2 with a height of 2.6 m. Figure 7a,b show a 3D model and overhead view of the room using AutoCAD 2024. The surface area of each biocompatible acoustic element was 0.48 m^2, and 12 units of 12 mm thickness were installed in the ceiling.

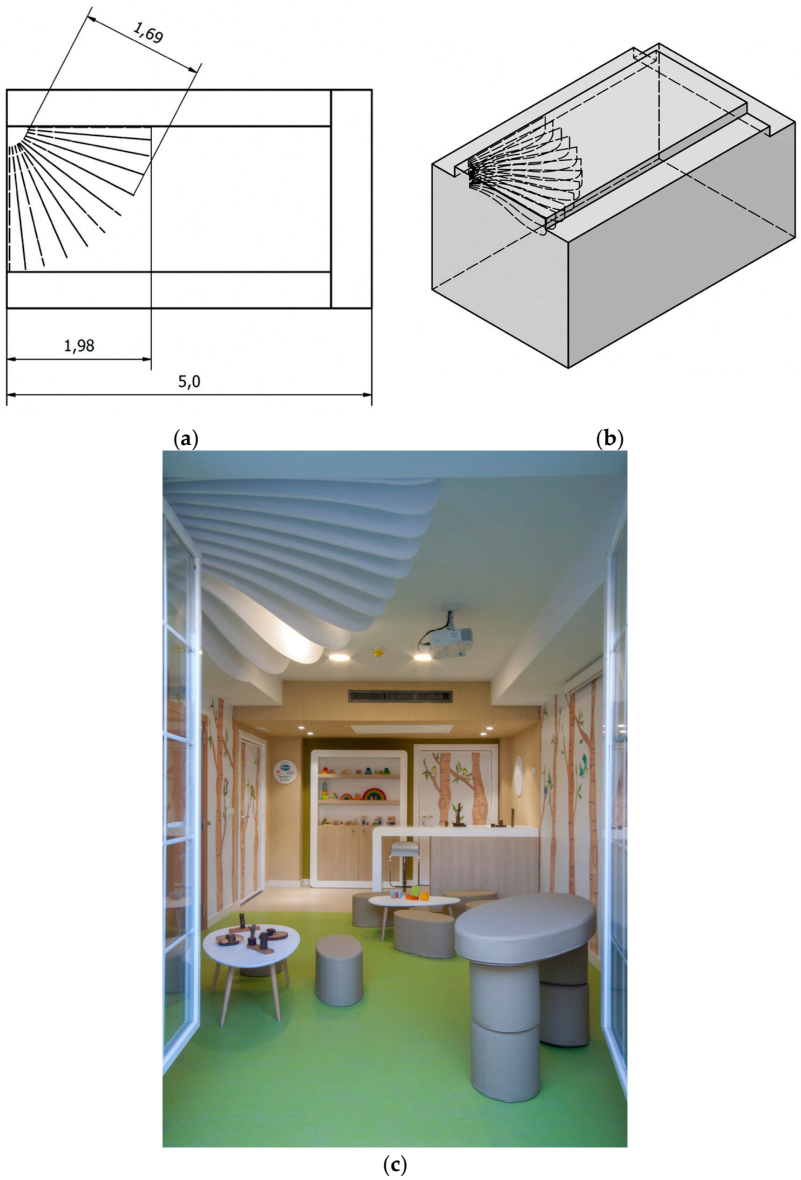

Figure 7. Case Study II, childcare room: (**a**) plan view; (**b**) rendered view; (**c**) aspect of the playroom of the Pediatric Oncology Department of the Hospital Universitario la Paz (Madrid, Spain) after reducing noise pollution and improving acoustic comfort.

The simulations, as in Case Study 1, were performed for the empty room and with the treatment based on the biocompatible material. The simulations predicted an average RT of 2.14 s in the bands of interest (500, 1000, and 2000 Hz), with an improvement of 1.4 s over the simulated RT of the empty room. As for the C50, STI, and %Alcons values in the areas of interest, these were −6.3 dB, 0.41, and 19.82%, respectively, showing a low intelligibility of the empty room.

Simulations were then carried out with an acoustic treatment to improve noise pollution and acoustic comfort using the biocompatible material. More specifically, 5.76 m^2 of biocompatible material was installed on the ceiling. The acoustic solution was installed perpendicularly on the surface using mounting glue. Then, taking the same considerations as the previous study, values of RT, C50, and STI %Alcons were calculated. Figure 8a shows that the simulated model predicted an RT reduction of 1.68 s at 500 Hz, 1.8 s at 2000 Hz, and 1.78 s at 4000 Hz. Consequently, following the inclusion of the acoustic material under study in the model, the average RT in the main room after acoustic treatment was 0.74 s. The material's performance reconfirmed laboratory sound absorption tests. The reverberant field was significantly reduced. In addition, the C50 was increased up to 8.4 dB, the STI intelligibility factor was improved by 0.4, and the %Alcons was reduced to 14.68%. Figure 8b,c illustrate the C50 and STI values in the areas of interest. Table 4 presents a summary of the improvements in noise pollution and acoustic comfort obtained with the biocompatible material for Case Study II.

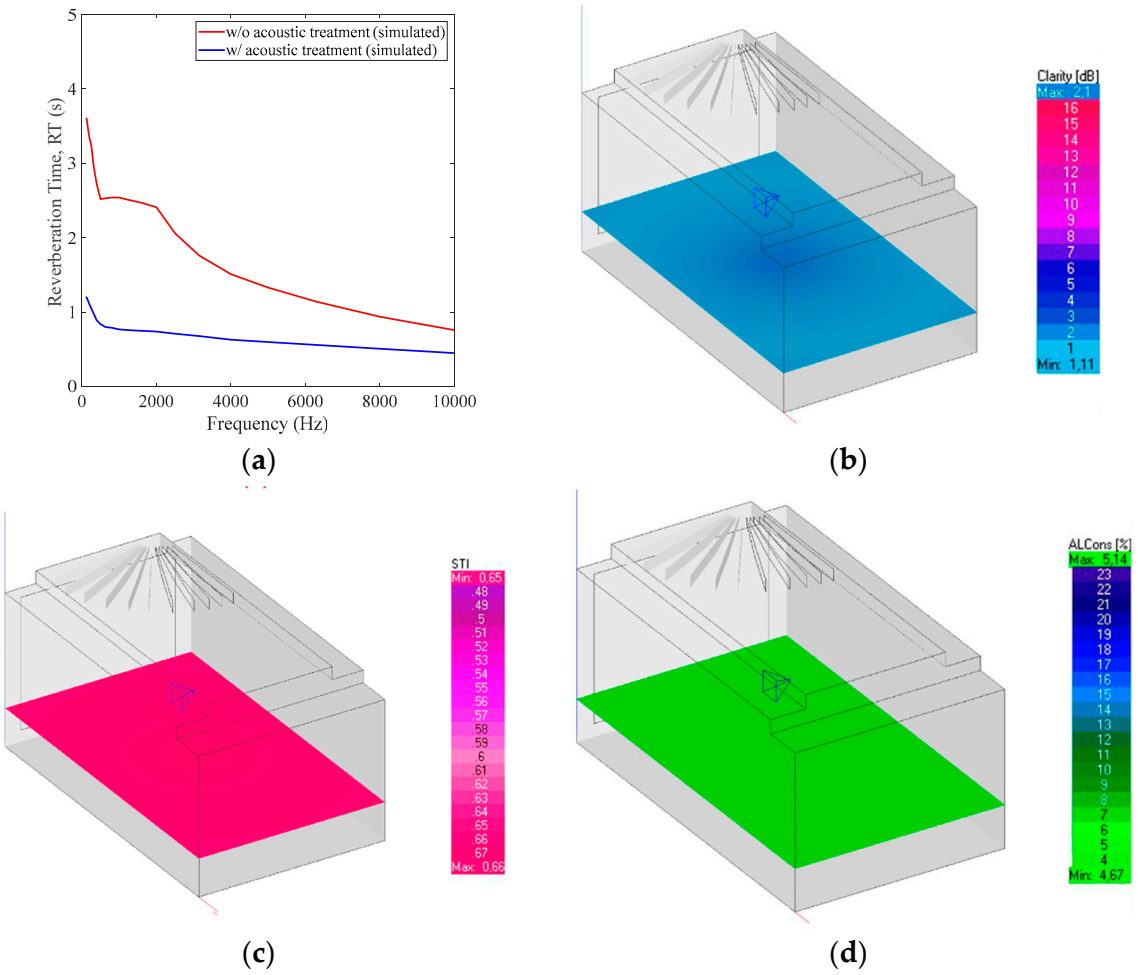

Figure 8. Noise pollution reduction and improvement of acoustic comfort in Case Study II: (**a**) Comparison of the predicted RT for the configurations without acoustic treatment (continuous magenta line) and with acoustic treatment (continuous cyan line); (**b**) C50; (**c**) STI; and (**d**) %Alcons distribution over the useful space.

Table 4. Improvements in terms of acoustic comfort achieved in the childcare room for Case Study II.

Parameter	Without Acoustic Treatment	With Acoustic Treatment
RT (s)	2.14	0.74
C50 (dB)	−6.3	2.1
STI	0.41	0.8
%Alcons (%)	19.82	5.14

The room without acoustic treatment presented an improved acoustic performance, with an RT of 2.14 s, a C50 of −6.3 dB, an STI of 0.41, and a %Alcons of 19.82%, all classified as "poor" or "acceptable" according to the objective rating of speech intelligibility by the speech transmission index [61]. After acoustic treatment with the biocompatible material, significant improvements were observed: RT was reduced to 0.74 s, C50 increased to 2.1 dB, STI improved to 0.8, and %Alcons decreased to 5.14%, rated as "good", "excellent" and "acceptable", respectively. As in the previous case, noise pollution and acoustic comfort improved.

4. Discussion

Research indicates that noise adversely affects mental and physiological health, with hospital noise levels frequently surpassing recommended thresholds. While passive acoustic absorbers are effective in noise reduction, their inorganic composition and petrochemical origins pose health risks. Consequently, there is a growing focus on developing eco-friendly, low-toxicity, and biocompatible materials, including those derived from microplastic waste, which exhibit desirable acoustic properties. This work presents a PET-based acoustic absorbent material made from plastic bottles. The material under study demonstrated (i) fungal resistance (after inoculation and incubation for 28 days), (ii) low VOC (less than 2–3 $\mu g/m^3$ after 28 days of incubation), and (iii) bioinert properties (24 h incubation of 661W cell line). In an assay performed with the 661W cell line, the material under study showed no interference with cell morphology, adhesion, or proliferation. As a result, our findings indicate that the material under study exhibited biocompatible properties that were deemed suitable for operation in both healthcare and biological environments.

The use of biocompatible absorbent materials in biomedical applications has the potential to be highly beneficial. For instance, the noise generated by biomedical equipment has emerged as a significant risk factor for the hearing health of healthcare workers [5,8]. By implementing passive noise reduction techniques, an average acoustic noise reduction of approximately 10.9 dB is achieved within the frequency range of 0 to 3 kHz [62]. In addition to biomedical device applications, biocompatible absorbent materials can transform hospitals into healthy environments by acting on their soundscape [63]. The primary sources of noise in hospitals are the alarms of biomedical devices in intensive care units (ICUs) and operating rooms, as well as conversations between individuals in shared spaces [64,65]. It was demonstrated that modifications to the indoor soundscape can reduce both physical and psychological stress in patients, thereby enhancing their overall health and well-being [66].

Moreover, experiments in a reverberant chamber according to ISO 10534-2 and ISO 354 standards showed the good sound absorption performance of the proposed biocompatible material, especially in the case of plenum configurations, thus encouraging its applicability in a real scenario. The biocompatible material demonstrated excellent thermal conductivity and thermal resistance in subsequent tests.

In this context, two case studies were conducted to reduce noise pollution and improve acoustic comfort. In the first case, the building exhibits dimensions and characteristics analogous to those of a healthcare environment. In addition to common areas, waiting rooms corridors, or stairwells, it contains a substantial space dedicated to administrative tasks and meeting areas for workers. Although the insulation of partitions adjacent to corridors and common areas and the insulation properties of doors have been described as important elements, RT is one of the critical acoustic indicators of acoustic comfort [67]. After conditioning the general space with the biocompatible material (refer to Section 3.4.1

for details), RT was reduced by 5.87 s at 500 Hz, 7.2 s at 2000 Hz, and 4.25 s at 4000 Hz. In the second case study, a childcare room of the Pediatric Oncology Department of the Hospital Universitario la Paz (Madrid, Spain) was simulated, and the results supported the previous study. The RT decreased in 1.68 s at 500 Hz, 1.8 s at 2000 Hz, and 1.78 s at 4000 Hz. In general terms, RT and background noise have been associated with a reduction in medical errors and improvement in both patient safety and the sound perception of healthcare workers [65,68,69]. Reducing the RT of patient and staff resting rooms promotes deep sleep and reduces nocturnal arousal events [70].

Furthermore, speech intelligibility is critical in healthcare environments, as it affects acoustic comfort and reduces unhealthy vocal stress for both patients and healthcare workers [71–73]. Parameters such as C50, STI, and %Alcons are key indicators for assessing this intelligibility [59,74,75]. A high C50 indicates better speech clarity, STI reflects the quality of speech transmission, and low %Alcons values indicate better speech understanding. In both case studies, the use of biocompatible acoustic material significantly improved speech intelligibility, enhanced acoustic comfort, and reduced stress and auditory fatigue for healthcare workers and patients.

5. Conclusions

To assess the material's biocompatibility, a series of tests, including antifungal resistance, VOC emission assessments, and cell viability experiments, were conducted, and all yielded positive results. Additionally, we measured the thermal conductivity, thermal resistance, and sound absorption coefficients of the proposed materials in diffuse field conditions to quantify the improvement in terms of noise pollution and acoustic comfort. The findings indicate that these eco-friendly, low-toxicity, and biocompatible materials can significantly enhance noise reduction and acoustic comfort in healthcare environments, contributing to improved patient and staff well-being. Next, two case studies were carried out. The first case was a building with a high number of elements common to hospital environments, such as a large lobby, common areas, offices, and meeting rooms. The application of biocompatible materials allowed a significant reduction in RT and improved speech intelligibility (C50, STI, and %Alcons). The second case, performed at the Pediatric Oncology Department of the Hospital Universitario La Paz in Madrid, confirmed the previous results. The results of the case studies supported the laboratory experiments. In conclusion, the biocompatible material reduced noise pollution and improved acoustic comfort, highlighting the potential of recycled acoustic panels made from plastic bottles and PET felt composites as reliable vibroacoustic solutions in healthcare and biological environments.

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