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Upcycling Textile Waste into Sustainable Acoustic Panels

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Abstract

Textile waste represents a growing environmental challenge, while also offering opportunities for material recovery and the development of higher-value recycled products. This study investigated the potential of post-consumer textile waste for the production of sound-absorbing acoustic panels. Five textile fiber compositions were evaluated: cotton, polyester, wool, linen, and a mixed blend consisting of 50% polyester, 30% cotton, 10% wool, 5% linen, and 5% other fibers. The panels were produced using a biopolymer binder and tested using an AFD 1000 impedance tube. The measurement software generated frequency-resolved sound absorption data from 6.25 to 6393.75 Hz at 6.25 Hz intervals; however, only the validated frequency range of 100–4000 Hz was included in the analysis. Three cylindrical specimens with a diameter of 40 mm were prepared from each material type. Sound absorption coefficients were analyzed across low- (100–250 Hz), mid- (250–1000 Hz), and high-frequency (1000–4000 Hz) ranges, and statistical differences between materials were assessed using one-way ANOVA and Tukey's HSD post hoc test. The results showed no statistically significant differences between fiber types at low frequencies. In contrast, significant differences were observed in the mid- and high-frequency ranges. Cotton achieved the highest mean absorption coefficient in the mid-frequency range ($\alpha = 0.747$), while polyester and wool performed best at high frequencies, with mean absorption coefficients of 0.913 and 0.850, respectively. Polyester showed the highest overall acoustic performance across the analyzed frequency range, with a mean absorption coefficient of $\alpha = 0.824$. These findings demonstrate that post-consumer textile waste can be upcycled into functional acoustic materials, supporting circular economy principles and offering a potential alternative to conventional mineral-based sound absorbers in interior and construction applications.

Keywords: textile waste; acoustic materials; sound absorption; biopolymer binder; circular economy; sustainable construction; recycled fibers

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1. Introduction

In recent years, both the European Union and the global community have increasingly emphasized the transition toward a sustainable and environmentally friendly economy. This shift is strongly aligned with the United Nations Sustainable Development Goals, which aim to address complex social, environmental, and economic challenges while promoting a more resilient and resource-efficient future [1–3]. Within this framework, the use of recycled and repurposed materials has become an essential priority, supporting waste reduction, resource conservation, and climate change mitigation [4,5].

The textile industry represents one of the most resource-intensive and environmentally impactful sectors worldwide. In the European Union alone, approximately 9.35 million tonnes of textile waste are generated annually [6]. Although research indicates that up to 95% of these wastes could be effectively recycled into valuable materials, current recycling rates remain low, with only about 25% being reprocessed in practice [7]. This discrepancy highlights both the urgency and potential for developing innovative approaches that extend the life cycle of textile products while reducing environmental burdens.

The reuse of textile waste within material science and engineering has received growing attention, particularly in the development of acoustic solutions. Over the last decade, recycled materials have been explored as alternatives to conventional sound-absorbing products. Studies demonstrate that sustainable acoustic materials often exhibit comparable or even superior sound absorption characteristics to conventional insulators such as mineral wool or polyurethane foams, which are derived from non-renewable and synthetic sources [8–10]. While these traditional materials are valued for their low thermal conductivity and reliable acoustic performance, their production is associated with high environmental costs, including high energy consumption, greenhouse gas emissions, and waste generation [11].

Textile materials absorb sound mainly because of their porous fibrous structure. When sound waves enter the spaces between the fibers, the air inside these pores begins to oscillate. Friction between the moving air and the fiber surfaces, together with thermal losses, converts part of the sound energy into heat. Fibrous materials generally perform better at medium and high frequencies, while their low-frequency absorption is strongly influenced by panel thickness and the presence of an air gap [12–14]. Sound absorption depends on several physical characteristics of the material, including thickness, density, fiber diameter, pore structure, porosity, tortuosity, and airflow resistivity. Porosity describes the proportion of void space within the material, while tortuosity reflects how complex the pathways through these pores are. More irregular pathways increase the distance travelled by air through the material and can increase energy losses. However, high porosity alone does not necessarily ensure better sound absorption, as pore size, pore connectivity, and fiber arrangement also affect the acoustic response [13–16].

Airflow resistivity is considered one of the main parameters controlling the acoustic behaviour of fibrous materials. If the resistance is too low, air moves through the material with little energy loss. In contrast, very high resistance may cause more sound to be reflected from the surface. Effective sound absorption therefore requires a balance between an open pore structure and sufficient resistance to airflow. In recycled textile panels, this balance can be affected by fiber size, compaction, fiber distribution, and the amount of binder used [14–16]. Previous studies have shown that porosity, fiber size, and layer arrangement influence both airflow resistivity and sound absorption in nonwoven materials [15]. Research on recycled textile composites containing biopolymer binders has also demonstrated that porosity, tortuosity, airflow resistance, and binder properties contribute to their acoustic performance [16]. Therefore, differences between textile panels cannot be attributed to fiber composition alone, as the physical structure of the material must also be considered.

Textile waste streams include discarded clothing, upholstery, and post-industrial residues, all of which represent a serious challenge for waste management systems [17]. At the same time, they provide a unique opportunity to design high-value, functional products for the construction and interior sectors. Recent studies have highlighted the growing demand for effective noise control in various environments, ranging from office buildings and educational institutions to industrial facilities and cultural spaces such as music studios

and theaters. This trend reinforces the need for innovative, sustainable acoustic materials that combine technical performance with environmental responsibility [18–20].

Moreover, the integration of textile waste into construction materials directly supports the goals of the European Green Deal and the Circular Economy Action Plan, which promote long-lasting product design, reuse, and recycling while reducing the overall generation of waste [21]. Beyond technical benefits, such solutions deliver socio-economic and environmental advantages, including reduced landfill dependency, lower greenhouse gas emissions, and the creation of sustainable business opportunities in the circular economy sector [22,23]. Taken together, these perspectives demonstrate that utilizing textile waste in the development of acoustic materials not only addresses pressing environmental challenges but also contributes to advancing a circular and resource-efficient economy.

Although numerous studies investigated the acoustic properties of natural and recycled textile fibers, several important knowledge gaps remain. Most previous studies have focused on individual textile fractions, industrial textile residues, or synthetic fibers, while comparatively little information is available regarding the acoustic performance of post-consumer textile waste separated by fiber composition and bonded with biodegradable binders. Furthermore, direct comparisons between different textile fiber groups under identical manufacturing and testing conditions remain limited. The influence of fiber type on sound absorption performance across low-, mid-, and high-frequency ranges is therefore not yet fully understood. Addressing these gaps is essential for optimizing textile waste valorization pathways and supporting the development of sustainable acoustic materials within the circular economy.

The aim of this research is to develop sound-absorbing materials from textile waste using five different fiber compositions (wool, polyester, linen, cotton, and mixed fibers) and to determine their sound absorption coefficients across the full frequency range (100–4000 Hz). The study further seeks to evaluate and compare their performance in noise reduction, with the goal of identifying the most effective compositions for application as sustainable acoustic materials.

2. Results

The study examined five different samples of sound-absorbing materials with the aim of comparing their acoustic absorption performance across frequency ranges from 100 Hz to 4000 Hz.

2.1. Sound Absorption at Low Frequencies (100–250 Hz)

To evaluate the sound absorption performance of different textile fibers at low frequencies (100–250 Hz), absorption coefficients were determined for five types of textile materials: linen, cotton, mixed fiber, wool, and polyester. Statistical analysis was carried out using one-way analysis of variance (ANOVA), supported by descriptive statistics and data visualization.

The obtained p-value (0.981) indicates that no statistically significant differences exist between the absorption values of the tested textile types ($p > 0.05$). The low F-value (0.100) further suggests that the variation between group means is minimal relative to the within-group variation. Therefore, it can be concluded that fiber type does not have a substantial effect on sound absorption properties within this frequency range. The absence of statistically significant differences indicates that fiber composition had only a negligible influence on sound absorption performance at low frequencies. This finding suggests that the overall panel structure, thickness, and density may play a more important role than fiber type within this frequency range. The scatter observed in the 100–250 Hz range is mainly related to the increase in the sound absorption coefficient with increasing frequency.

As the box plots include all values across this frequency interval, the observed spread reflects frequency-dependent changes rather than measurement variability alone.

Descriptive statistics complement these findings (see Figure 1). Despite slight differences in the value ranges, the mean and median values are similar across all materials. The mixed fiber sample exhibited the highest mean absorption coefficient (0.183), while polyester showed the lowest (0.143); however, these differences are not statistically significant.

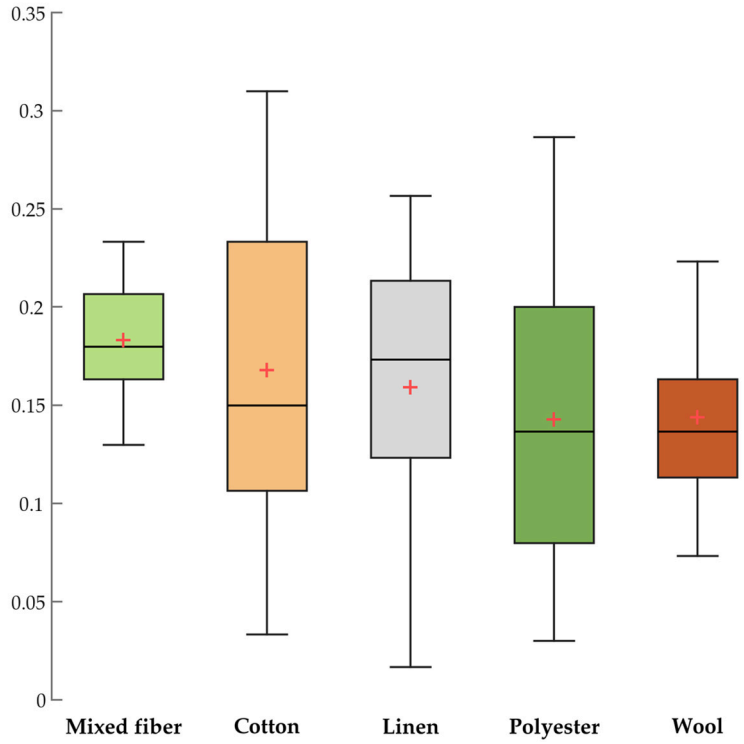


Figure 1. Distribution of sound absorption coefficients for different textile types in the frequency range of 100–250 Hz. Boxes represent the interquartile range (IQR), horizontal lines inside the boxes indicate the median, "+" symbols indicate the arithmetic mean, and whiskers extend to the most extreme values within 1.5 × IQR.

2.2. Sound Absorption at Mid Frequencies (250–1000 Hz)

To assess the ability of different textile materials to absorb sound at mid frequencies (250–1000 Hz), sound absorption coefficients were calculated, and an ANOVA was performed, followed by post hoc comparisons using the Tukey HSD test.

The very low p-value (9.70×10^{-8}) indicates statistically significant differences in absorption performance between at least two textile types ($p < 0.05$). The relatively high F-value (21.24) further confirms that the variation between groups is considerably greater than the variation within groups, demonstrating that fiber type plays a critical role in acoustic absorption effectiveness within this frequency range. The observed differences are not only statistically significant but also practically relevant. Cotton exhibited a mean absorption coefficient approximately 2.8 times higher than the mixed-fiber material and 2.5 times higher than linen, demonstrating the strong influence of fiber composition on acoustic performance in the mid-frequency range.

Tukey's HSD post hoc analysis identified seven statistically significant pairwise differences: Mixed fiber–Cotton, Mixed fiber–Polyester, Cotton–Linen, Cotton–Polyester, Cotton–Wool, Linen–Polyester, and Polyester–Wool.

These results highlight that cotton exhibits substantially higher absorption coefficients compared to most other materials, particularly in relation to linen and mixed fibers.

Polyester also differs significantly from wool and mixed fibers, underscoring the influence of fiber composition on acoustic absorption properties.

The data visualization (see Figure 2) shows that cotton not only has the highest median value but also the broadest distribution, whereas linen and mixed fibers form a group with lower coefficients and narrower value ranges. These patterns are consistent with the statistical findings and emphasize the strong absorption performance of cotton in the mid-frequency domain.

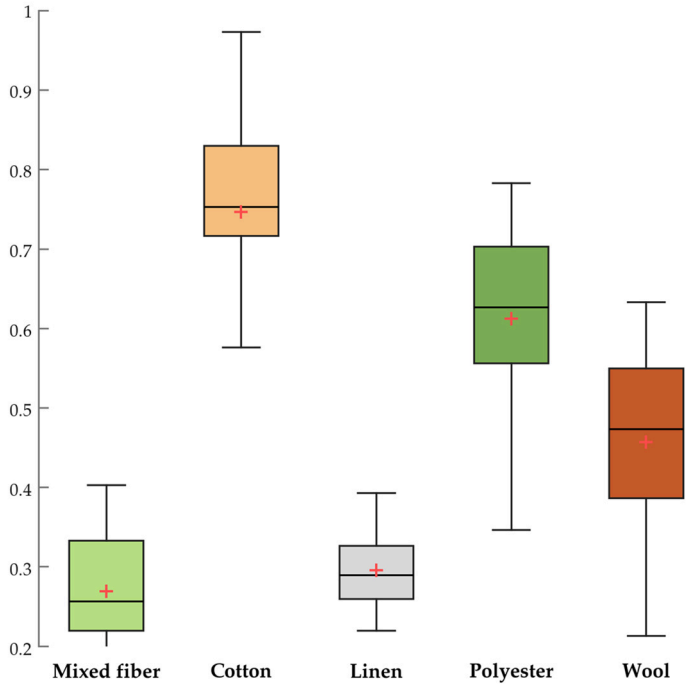


Figure 2. Distribution of sound absorption coefficients for different textile types in the frequency range of 250–1000 Hz. Boxes represent the interquartile range (IQR), horizontal lines inside the boxes indicate the median, "+" symbols indicate the arithmetic mean, and whiskers extend to the most extreme values within 1.5 × IQR.

2.3. Sound Absorption at High Frequencies (1000–4000 Hz)

To investigate the sound absorption performance of various textile materials at high frequencies (1000–4000 Hz), an ANOVA was performed, followed by pairwise comparisons using the Tukey HSD test.

The low p-value (1.51×10^{-8}) confirms that there are statistically significant differences in absorption coefficients among the tested textiles ($p < 0.05$). The high F-value (21.94) indicates that the variation between groups is considerably greater than within groups, highlighting the strong influence of fiber type in this frequency range.

The Tukey HSD post hoc analysis identified statistically significant pairwise differences between several material groups in the 1000–4000 Hz frequency range. The results showed that linen differed substantially from the materials with the highest absorption coefficients, particularly polyester and wool. Differences involving cotton and mixed fibers were also observed. However, wool and polyester did not differ significantly from each other, indicating similar acoustic behavior in the high-frequency range.

The data visualization (see Figure 3) illustrates that polyester and wool exhibit the highest absorption coefficients, with median values above 0.8, reflecting highly efficient sound absorption at higher frequencies. Linen displays the lowest mean absorption coefficient ($\alpha = 0.551$), followed by mixed fibers ($\alpha = 0.575$). Cotton shows an intermediate mean absorption coefficient of 0.750. This trend is consistent with the statistical results and

demonstrates that fiber composition plays a decisive role in acoustic absorption performance at high frequencies.

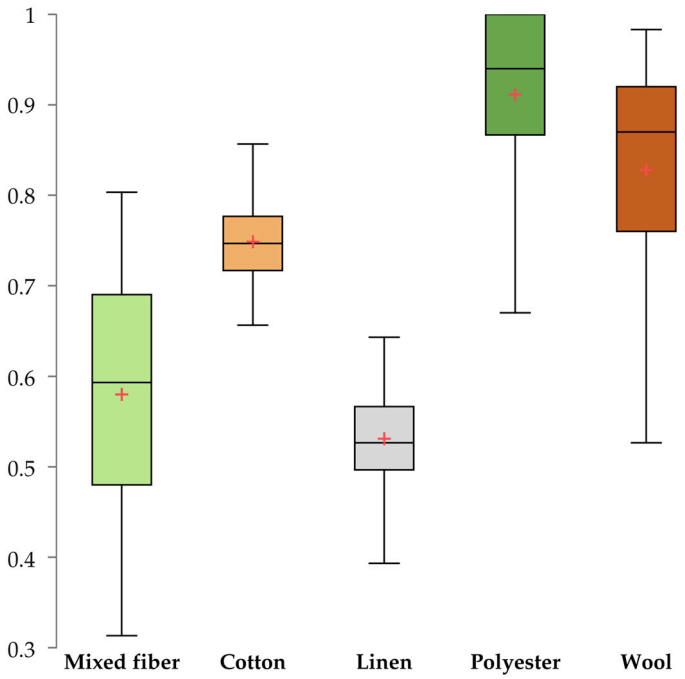


Figure 3. Distribution of sound absorption coefficients for different textile types in the frequency range of 1000–4000 Hz. Boxes represent the interquartile range (IQR), horizontal lines inside the boxes indicate the median, "+" symbols indicate the arithmetic mean, and whiskers extend to the most extreme values within 1.5 × IQR.

2.4. Sound Absorption Coefficients Across the Full Frequency Range (100–4000 Hz)

Across the measured frequency range, the textile materials generally show an increase in the sound absorption coefficient (α) with increasing frequency; however, each material demonstrates a distinct absorption profile. At low frequencies of 100–250 Hz, all materials show relatively low and similar absorption values. Cotton exhibited a pronounced increase in sound absorption above approximately 250 Hz, reaching a local maximum between approximately 400 and 500 Hz. Although cotton exhibited excellent absorption in the mid-frequency range, its absorp-tion coefficient gradually decreased above approximately 1000 Hz, whereas polyester and wool continued to increase. After this peak, α decreases slightly and then remains relatively stable at a moderate-to-high level across the mid- and high-frequency range. Polyester shows a substantial increase in sound absorption with increasing frequency and demonstrates the best overall performance, reaching an absorption coefficient close to $\alpha = 1$ at higher frequencies. Wool also shows a gradual increase in absorption across the entire frequency range and reaches high absorption values in the upper-frequency region, although slightly lower than those of polyester. In contrast, linen shows a more gradual increase in absorption and remains the weakest sound absorber over most of the measured range, with α values generally not exceeding 0.65. The mixed-fiber material exhibits intermediate behavior: its absorption values are generally higher than those of linen but lower than those of cotton, wool, and polyester in the high-frequency range. The greatest differences between materials are observed above approximately 2000–2500 Hz, where polyester and wool show the highest absorption efficiency, while linen remains at considerably lower values (see Figure 4).

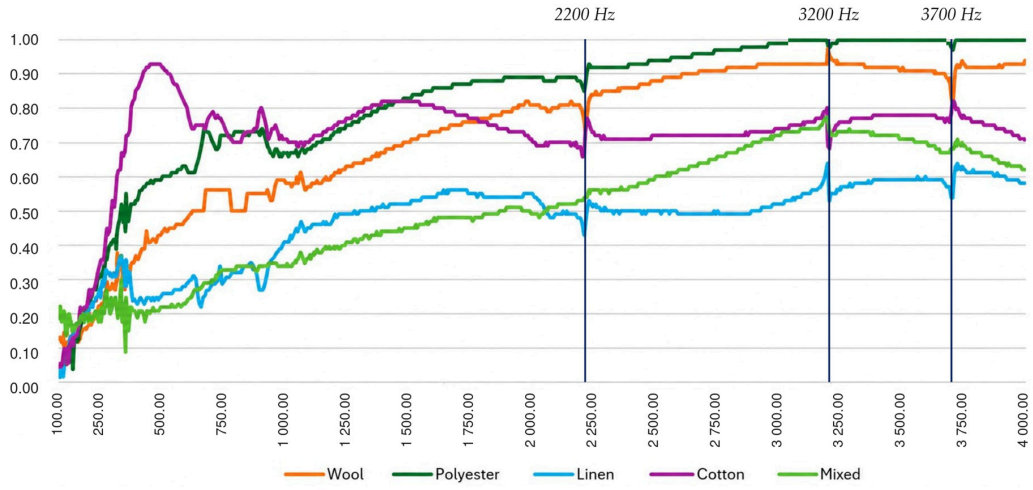


Figure 4. Sound absorption coefficients across the full frequency range (100–4000 Hz). Vertical lines indicate measurement-system-related drops observed at 2200, 3200, and 3700 Hz.

Small drops occurred at approximately 2200, 3200, and 3700 Hz for all materials. Since they appeared at the same frequencies in every measurement, they may be related to the measurement system rather than the materials themselves. The exact cause could not be confirmed; therefore, values at these frequencies should be interpreted with caution.

2.5. Mean Absorption Coefficients and Repeatability of Acoustic Measurements

To further evaluate the acoustic performance and repeatability of the measurements, the mean sound absorption coefficients and average standard deviations were calculated for each material and frequency range (see Table 1). The results provide a clearer overview of both material performance and measurement variability across low-, mid-, and high-frequency ranges.

Table 1. Mean sound absorption coefficient and average standard deviation (SD) by material and frequency range.

	Low Frequency (100–250 Hz)		**Mid Frequency (250–1000 Hz)**		**High Frequency (1000–4000 Hz)**		**Overall (100–4000 Hz)**	
Material	**Mean α**	**Mean SD**	**Mean α**	**Mean SD**	**Mean α**	**Mean SD**	**Mean α**	**Mean SD**
Wool	0.144	0.025	0.457	0.043	0.850	0.028	0.730	0.030
Polyester	0.143	0.031	0.612	0.050	0.913	0.025	0.824	0.029
Linen	0.159	0.013	0.296	0.013	0.551	0.013	0.471	0.013
Cotton	0.168	0.031	0.747	0.029	0.750	0.030	0.726	0.030
Mixed fibers	0.183	0.028	0.269	0.027	0.575	0.026	0.505	0.026

All textile-based materials showed relatively low absorption in the low-frequency range of 100–250 Hz, with mean absorption coefficients ranging from 0.143 to 0.183 (Table 1). The highest mean value in this range was observed for mixed fibers ($\alpha = 0.183$), followed by cotton ($\alpha = 0.168$) and linen ($\alpha = 0.159$). Polyester and wool showed the lowest mean values, with $\alpha = 0.143$ and $\alpha = 0.144$, respectively. However, the differences between materials were small, which is consistent with the limited low-frequency absorption typically observed for relatively thin fibrous materials. Clearer differences between materials were observed in the mid- and high-frequency ranges (Table 1). In the mid-frequency range, cotton showed the highest mean absorption coefficient ($\alpha = 0.747$), followed by polyester ($\alpha = 0.612$) and wool ($\alpha = 0.457$). Linen and mixed fibers showed lower absorption in this range, with mean

values of 0.296 and 0.269, respectively. Across the overall frequency range of 100–4000 Hz, polyester demonstrated the highest mean sound absorption coefficient (α = 0.824), followed by wool (α = 0.730) and cotton (α = 0.726). Mixed fibers showed a mean coefficient of 0.505, while linen had the lowest overall mean value of 0.471. Compared with linen, polyester achieved approximately 75% higher average sound absorption coefficient, highlighting its potential as a preferred textile waste fraction for acoustic panel production.

The average standard deviation values were generally low, ranging from 0.013 to 0.050 (Table 1). This indicates good repeatability of the acoustic measurements. The lowest variability was observed for linen, while the highest average standard deviation was recorded for polyester in the mid-frequency range. The slightly higher variability in some materials may be related to differences in fiber distribution, binder penetration, and the heterogeneous structure of shredded textile waste. Overall, the low standard deviation values suggest that the prepared samples showed stable and reproducible acoustic behavior.

2.6. Comparison of Textile Waste Samples with Mineral Wool and Rock Wool Across the Entire Frequency Range (100–4000 Hz)

To evaluate the suitability of the developed textile waste-based materials for sound absorption, their acoustic performance was compared with that of mineral wool and rock wool, which are commonly used as conventional sound-absorbing materials. The box plots presented in Figure 5 illustrate the distribution of sound absorption coefficients for the seven material groups across the frequency range of 100–4000 Hz. The distributions also indicate considerable overlap between wool, cotton, and mineral wool, suggesting comparable acoustic performance over substantial portions of the in-vestigated frequency range. Among the textile waste-based samples, polyester exhibited the highest mean absorption coefficient (α = 0.824), followed by wool (α = 0.730) and cotton (α = 0.726). Mixed fibers showed an intermediate mean value of 0.505, while linen had the lowest mean absorption coefficient among the textile samples (α = 0.471). The results indicate that polyester, wool, and cotton achieved acoustic performance approaching that of the conventional reference materials across parts of the analyzed frequency range. However, direct comparisons should be interpreted cautiously because the reference data were obtained from external sources and may differ in material thickness, density, structure, and measurement conditions.

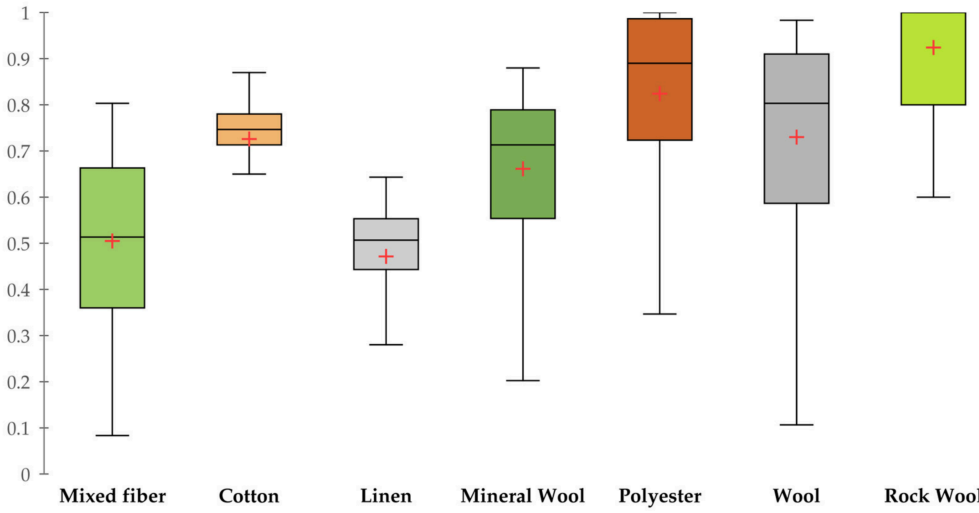


Figure 5. Distribution of sound absorption coefficients for different textile types, mineral wool, and rock wool across the frequency range of 100–4000 Hz. Boxes represent the interquartile range (IQR), horizontal lines inside the boxes indicate the median, "+" symbols indicate the arithmetic mean, and whiskers extend to the most extreme values within 1.5 × IQR.

3. Discussion

The results of this study indicate that textile waste-based panels can provide effective acoustic absorption, particularly in the mid- and high-frequency ranges. Cotton showed the highest efficiency in the mid-frequency range (250–1000 Hz), while polyester and wool achieved superior performance at high frequencies (1000–4000 Hz). These results are consistent with previous studies, where natural and synthetic fibers with porous and fibrous structures effectively dissipate sound energy through viscous and thermal interactions [24,25]. The obtained absorption coefficients above 0.7 at high frequencies support the potential of textile waste as a suitable feedstock for sustainable acoustic materials.

The acoustic performance of the developed panels was compared with that of similar recycled textile-based sound-absorbing materials reported in previous studies. Sound-absorbing boards produced from textile waste have demonstrated absorption coefficients ranging from approximately 0.7 to 0.9 at high frequencies [26]. Similarly, 50 mm thick panels made from recycled wool fibers and biopolymer binders showed absorption coefficients generally exceeding 0.5 above 500 Hz and 0.9 above 1000 Hz [27]. In the present study, the polyester- and wool-based panels achieved mean high-frequency absorption coefficients of 0.913 and 0.850, respectively, while cotton reached 0.750. These results indicate that the polyester- and wool-based panels fall within the upper performance range reported for comparable recycled textile materials. In contrast, the linen and mixed-fiber panels exhibited lower absorption, demonstrating the influence of fiber composition and internal structure on acoustic performance. However, direct numerical comparisons should be interpreted cautiously because the materials differed in fiber composition, binder type, density, airflow resistivity, and measurement conditions.

At low frequencies (100–250 Hz), no statistically significant differences were observed between textile types. This outcome corresponds with research showing that lightweight fibrous materials generally provide limited absorption at low frequencies due to their relatively low thickness and density [12]. Comparable results have been reported for recycled textile composites, where absorption performance increased steadily with frequency and reached values of 0.7–0.9 at higher ranges [26,28–30]. The present findings therefore align with the broader consensus that while recycled fibrous panels perform effectively in mid-to-high frequencies, their efficiency at low frequencies may require structural modifications, such as increased thickness or the use of multilayer configurations.

The comparison with conventional materials suggests that several textile waste-based panels reached absorption levels close to those reported for mineral wool and rock wool across parts of the tested frequency spectrum. Polyester and cotton samples, in particular, showed absorption values that were close to those of the reference materials, indicating their potential for further development as alternative acoustic products. Comparable outcomes have been reported in other studies, where alternative natural and recycled materials reached absorption levels close to or equivalent to conventional mineral-based products [31,32]. Such findings support further investigation of textile waste as an environmentally responsible alternative to non-renewable insulators.

The observed differences between fiber types can be explained by structural parameters such as density, porosity, and fiber morphology. Wool and polyester fibers, which are characterized by curled or irregular geometries, provide a more complex pore network that enhances sound wave dissipation, while linen, with a smoother and more rigid structure, showed significantly lower absorption efficiency. This observation is in agreement with research highlighting the importance of fiber morphology and binder type in determining acoustic performance [16,27]. The superior performance of polyester and wool at high frequencies suggests that specific textile waste fractions may be prioritized in the design of recycled acoustic panels to optimize performance.

The superior acoustic performance of polyester and wool can be attributed to their three-dimensional fiber morphology and the resulting pore structure. Curled and irregular fibers create a complex network of interconnected voids, increasing airflow resistance and enhancing viscous friction losses when sound waves propagate through the material. This mechanism promotes more efficient conversion of acoustic energy into thermal energy, particularly at higher frequencies.

Overall, the present results add to the growing evidence that textile waste can be transformed into functional acoustic panels with promising sound absorption performance. This highlights the potential dual benefits of such solutions: reducing the environmental burden of textile disposal and supporting circular economy principles through the creation of value-added products. By integrating textile waste into the construction sector, it is possible to reduce landfill dependency, conserve resources, and foster innovation in sustainable building materials [28,33,34]. The study therefore provides further evidence that recycled textile-based panels may represent a promising alternative in the field of acoustic materials.

3.1. Significance of the Results in the Circular Economy

The findings of this study demonstrate that textile fiber-based materials can provide substantial sound absorption, particularly in the mid- and high-frequency ranges. These insights are relevant not only within materials science and acoustics but also in the broader framework of the circular economy, where increasing attention is directed toward utilizing waste as a resource for the development of new products. Traditionally, textile waste has been classified as low-value materials destined for energy recovery; however, the present results show that it can be upgraded into high-value functional acoustic panels. This approach aligns with the objectives of the European Union's Circular Economy Action Plan, which emphasizes designing long-lasting products, promoting reuse and recycling, and reducing waste generation [22,35].

The textile industry is one of the most resource-intensive sectors, with high levels of water and energy consumption and significant greenhouse gas emissions [18]. Integrating textile waste into new, recycled construction materials reduces environmental impacts and fosters resource circulation in the building sector, consistent with the European Green Deal [36].

Moreover, the observed differences in absorption performance between fiber types enable the selection of the most suitable waste materials, enhancing both functionality and sustainability of the end product. Materials with strong sound absorption capacity—such as polyester and wool at high frequencies—can be applied in interior solutions, for example, in offices and public spaces, where mineral wool or polyurethane have traditionally been dominant. Overall, the results broaden the understanding of the technical properties of recycled materials and illustrate how scientifically grounded applications can accelerate the transition from a linear to a circular economy—one in which resources are used more efficiently, products have extended lifespans, and waste becomes the foundation for new solutions.

3.2. Implications for Textile Waste Recycling and Circular Economy

The results demonstrate a practical pathway for diverting post-consumer textile waste from landfilling and incineration into value-added construction materials. Textile waste is frequently characterized by low recycling rates due to the complexity of fiber blends and contamination issues. The production of acoustic panels offers an opportunity to utilize mixed and lower-quality textile fractions that are often unsuitable for closed-loop textile recycling. Such applications contribute to resource efficiency, waste reduction, and

product life extension, supporting the principles of the circular economy and sustainable material management.

3.3. Study Limitations

Several limitations should be acknowledged. First, the study evaluated acoustic performance under laboratory conditions using a limited number of specimens per material type. Second, only one panel thickness and binder content were investigated. Third, important material properties such as thermal conductivity, fire resistance, moisture durability, and long-term mechanical stability were not assessed. Finally, measurement-system-related drops occurred at 2200, 3200, and 3700 Hz; therefore, values at these frequencies should be interpreted with caution. Future research should address these aspects to support the practical implementation and commercialization of textile waste-based acoustic panels.

3.4. Future Research Perspectives

Future studies should investigate the influence of panel thickness, density, fiber particle size distribution, and alternative bio-based binders on acoustic performance. Additional research should include life cycle assessment, economic feasibility analysis, fire safety testing, and long-term durability evaluation. Such investigations would provide a more comprehensive assessment of the environmental and technical suitability of textile waste-based acoustic materials.

3.5. Environmental Benefits of Textile Waste Valorization

The utilization of post-consumer textile waste for acoustic panel production provides several environmental benefits. First, it diverts textile waste from landfill disposal and incineration, reducing associated environmental impacts. Second, the replacement of virgin raw materials with recycled fibers decreases demand for resource-intensive production processes. Third, the use of biodegradable binders further improves the environmental profile of the developed materials. Considering the growing quantities of textile waste generated globally, the development of value-added products such as acoustic panels represents an effective strategy for increasing material circularity and reducing waste management burdens.

Based on the developed manufacturing process, approximately 1.3 L of shredded textile waste was incorporated into each experimental panel. This demonstrates the potential for converting significant quantities of post-consumer textile waste into value-added acoustic products. Scaling the process to industrial production could contribute substantially to textile waste diversion and resource recovery.

4. Materials and Methods

4.1. Textile Waste Collection and Preprocessing

The textile waste employed in this study was supplied by a municipal waste management company in Latvia, responsible for the collection of post-consumer textiles from households within the Vidzeme waste management region. This collection scheme provides residents with a sustainable, circular economy-based option for the disposal of unwanted textile products. Before experimental use, the collected textiles were subjected to manual inspection in order to remove non-textile impurities, including buttons, zippers, plastic fragments, and other rigid elements typically present in clothing and household fabrics. This procedure was essential to ensure feedstock homogeneity and to prevent external contaminants from influencing subsequent processing steps or the performance of the fabricated materials.

Following this preliminary sorting, the textile waste was classified into four predominant fiber groups—cotton, polyester, wool, and linen—reflecting the most common fibers present in consumer products and post-consumer waste streams. Each fiber category was mechanically shredded using an industrial dual-shaft shredder (ST-25; Shred-Tech, Cambridge, ON, Canada), producing fragments of appropriate size for panel fabrication. The resulting particles primarily ranged from 8 to 15 mm, with an overall size distribution between approximately 4 and 22 mm. To improve consistency, oversized and undersized fractions were removed by sieving. The entire process can be seen in Figure 6.



Figure 6. Manual sorting of textile waste to remove metal, plastic, and other non-textile impurities, followed by mechanical shredding with an industrial shredder.

The processed fibers were subsequently stored separately according to fiber type in sealed 30 L polyethylene bags. Storage was carried out under stable indoor conditions (temperature maintained at ~20 °C, relative humidity below 60%) in a dry and well-ventilated environment. These measures were taken to reduce moisture uptake and microbial activity, thereby preserving the structural integrity of the fibers prior to sample preparation.

4.2. Preparation of Biopolymer Binder

A biodegradable biopolymer binder was prepared to serve as a flexible and non-toxic adhesive for producing sound-absorbing composites. The resulting binder material is classified as thermoplastic starch plasticized with glycerol, formed through starch gelatinization in the presence of water and acetic acid, where glycerol acts as a plasticizer and provides flexibility. The formulation was optimized for one experimental unit, corresponding to approximately 1.3 L of shredded textile material. The mixture was composed of 200 mL of distilled water (200 g) as the liquid base, 60 mL of corn starch (Mango Spices, Riga, Latvia) (36 g) acting as the structural component and main adhesive, 13 mL of 9% vinegar (HAR, Baltezers, Latvia) (13.1 g) to facilitate starch gelatinization, and 26 mL of glycerol (STAFOR, Riga, Latvia) (33 g) to provide elasticity and prevent brittleness.

The preparation procedure began with heating distilled water in a stainless-steel pot to about 60 °C, avoiding boiling. Corn starch was slowly introduced into the warm water with continuous stirring to prevent clumping. Once the starch had dissolved, vinegar and glycerol were added while mixing was maintained. The suspension was kept on the hot plate and stirred until it thickened into a homogeneous gel-like binder, indicating that gelatinization was complete.

After preparation, the biopolymer was transferred into a clean container and sealed in a glass jar until use. The required equipment included a digital scale with an accuracy of ±0.1 g, a 200 mL laboratory cylinder, a stainless-steel pot with an electric hot plate, and a metal spoon or spatula for mixing.

4.3. Fabrication of Acoustic Samples

Five different material specimens were developed in this study to examine how various combinations of textile fibers and binder influence acoustic performance. All samples were prepared using biopolymer as the sole binding agent, while each specimen incorporated a distinct fiber type: cotton, polyester, wool, linen, or a mixed textile composition consisting of 50% polyester, 30% cotton, 10% wool, 5% linen, and 5% other fibers. The summary of the materials is presented in Table 2, while the varieties of textiles included in the research are shown in Figure 7.

Table 2. Summary of the study samples.

Sample No.	Textile Type	Binder
1	Cotton	Biopolymer
2	Polyester	Biopolymer
3	Wool	Biopolymer
4	Linen	Biopolymer
5	Mixed composition	Biopolymer

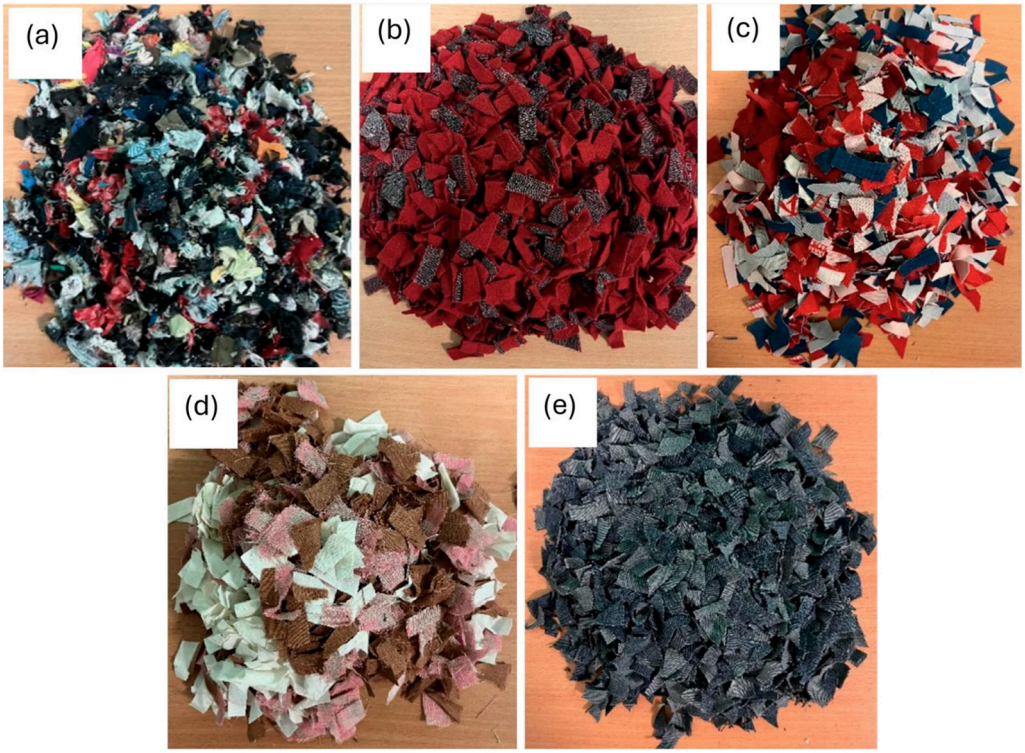


Figure 7. Varieties of textiles included in the research. (**a**) mixed composition: 50% polyester, 30% cotton, 10% wool, 5% linen, and 5% other textiles; (**b**) wool; (**c**) polyester; (**d**) linen; (**e**) cotton.

The fabrication of the experimental acoustic materials began with the construction of a wooden mold containing two compartments. The mold was assembled from wooden slats and plywood panels. Each compartment had internal dimensions of 12 × 15 × 5 cm, corresponding to a surface area of 180 cm^2 and a volume of 900 cm^3 (see Figure 8).

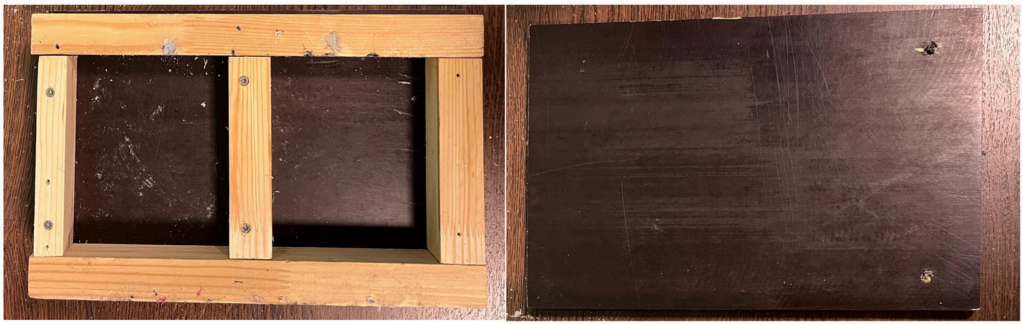


Figure 8. Wooden Mold for the Experiment.

Five experimental specimens were produced using different types of textile fibers in order to assess how fiber composition influences the material's structure and its potential acoustic properties. For all samples, a pre-prepared biopolymer mixture served as the binder and was combined with shredded textiles (1.3 L per specimen, particle size 0.5–2 cm). Each mixture was prepared individually to ensure uniform impregnation of the fibers with the binder. After thoroughly mixing the binder with the textile fibers, each blend was placed into a separate mold, pressed, and leveled. The specimens were then left to dry at room temperature for 48 h, allowing the biopolymer to fully harden and form stable, homogeneous structures. All preparations were carried out under identical conditions to ensure that differences in the physical and acoustic properties of the final products could be attributed solely to the type of fibers used. The fabricated specimens are presented in Figure 9.

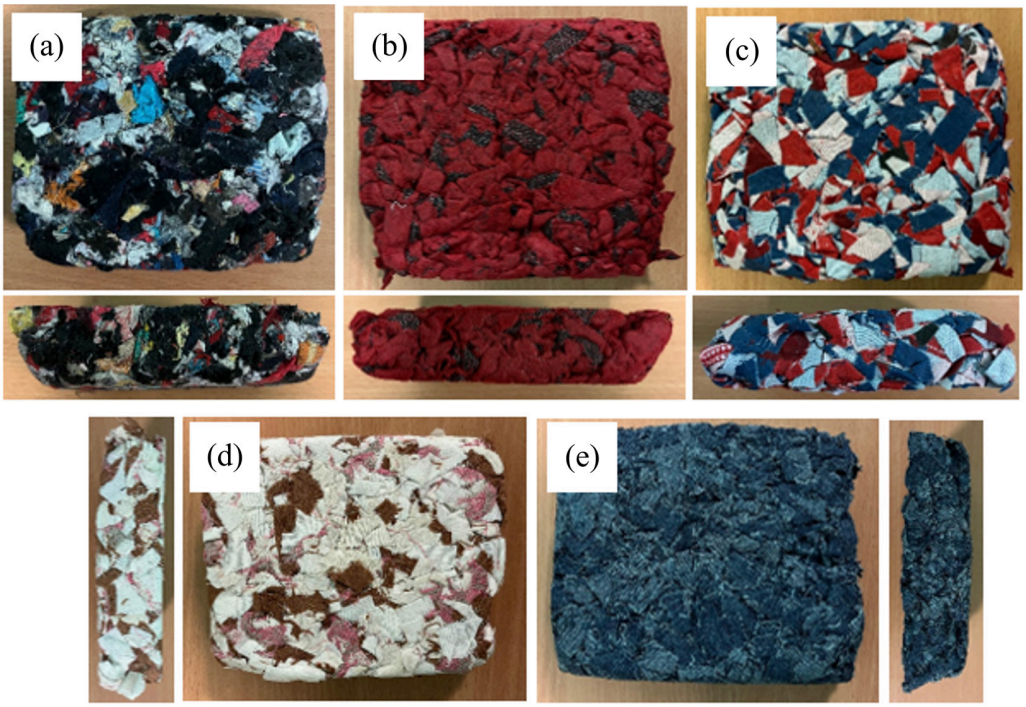


Figure 9. Developed samples with cross-sectional representation. (**a**) mixed composition: 50% polyester, 30% cotton, 10% wool, 5% linen, 5% other fibers; (**b**) wool; (**c**) polyester; (**d**) linen; (**e**) cotton.

After drying, the prepared panels differed in compactness, surface structure, and apparent porosity. The binder content was kept constant at 15 wt% for all samples, so the observed differences were mainly related to the textile fiber type and the resulting panel structure. Wool-based panels had the lowest density (175 $\pm$ 9 kg·m^{-3}) and the

highest estimated porosity (88 ± 3%), forming a relatively open and irregular structure with visible surface cavities. This structure may partly explain the strong sound absorption observed for wool at higher frequencies. In contrast, linen-based panels were the densest (220 ± 10 kg·m^{-3}) and had the lowest estimated porosity (78 ± 3%), resulting in a more rigid structure with visible fiber bundles. This is consistent with the lower acoustic performance of linen compared with the other materials. Cotton, polyester, and mixed-fiber panels showed intermediate structural characteristics. Cotton had a density of 190 ± 10 kg·m^{-3} and an estimated porosity of 85 ± 3%, with a soft and slightly uneven surface containing visible short fibers. Polyester was slightly denser (210 ± 12 kg·m^{-3}) and less porous (80 ± 4%), forming a smoother and more compact panel structure. The mixed-fiber panels had a density of 200 ± 10 kg·m^{-3} and an estimated porosity of 83 ± 3%, with a heterogeneous surface caused by the combination of different fiber types. These structural differences were considered relevant for interpreting the measured sound absorption behavior. A summary of the main physical properties of the prepared panels is provided in Table 3.

Table 3. Summary of the physical properties of the prepared samples.

Material	Nominal Panel Thickness, mm	Apparent Density, kg·m^{-3}	Estimated Porosity, %
Wool	50	175 ± 9	88 ± 3
Polyester	50	210 ± 12	80 ± 4
Linen	50	220 ± 10	78 ± 3
Cotton	50	190 ± 10	85 ± 3
Mixed fibers	50	200 ± 10	83 ± 3

Determination of Apparent Density and Calculated Estimated Porosity

The apparent density of the prepared panels was determined after drying. The dry mass (m_d) was measured using a digital balance (EMB 6000-1; KERN & SOHN GmbH, Balingen, Germany) with an accuracy of ±0.1 g. The geometrical volume of each rectangular panel was calculated using the following equation [37]:

$$V = L \times W \times T \quad (1)$$

where

L—length (m)

W—width (m)

T—thickness (m)

The dimensions of each panel were measured at five different locations using a digital caliper (MarCal 16 EWR, model 4103068; Mahr GmbH, Göttingen, Germany) with an accuracy of ±0.05 mm, and the average values were used in the calculations.

The apparent density was calculated as

$$\rho_b = \frac{m_d}{V} \quad (2)$$

where

m_d—dry mass of the panel (kg);

V—geometrical volume (m^3).

The water-accessible open porosity was determined using the water absorption method. Specimens were fully immersed in distilled water for 24 h at room temperature (20 ± 2 °C). After immersion, the specimen surfaces were wiped with a wet cloth to remove excess surface water and weighed immediately to obtain the saturated mass

(m_s). The open porosity was calculated from the difference between the saturated and dry masses, considering the density of water, according to the following equation [37]:

$$\phi = \frac{m_s - m_d}{\rho_w \times V} \quad (3)$$

where

m_s—mass of the water-saturated specimen (kg);
m_d—dry mass (kg);
p_w—density of water (kg·m^{-3});
V—geometrical volume of the specimen (m^3).

This calculation assumes that the absorbed water corresponds to the volume of interconnected pores accessible from the specimen surface, that the specimen volume remains unchanged during immersion, and that no dissolution or loss of material occurs. The calculated values therefore represent estimated water-accessible open porosity rather than total porosity, as closed or incompletely saturated pores are not included.

For each material type, three specimens were analyzed. The apparent density and estimated open porosity values are reported as the mean ± standard deviation (SD). The SD represents the variability among the three replicate specimens, including variability related to measurement repeatability and material heterogeneity. The instrumental accuracy was ±0.1 g for mass measurements and ±0.05 mm for dimensional measurements.

4.4. Acoustic Measurements

For the sound absorption tests, circular specimens with a diameter of 40 mm were cut from the fabricated materials using a sample cutting blade (see Figure 10). Three specimens were prepared from each material type, resulting in a total of 15 samples for the acoustic measurements.

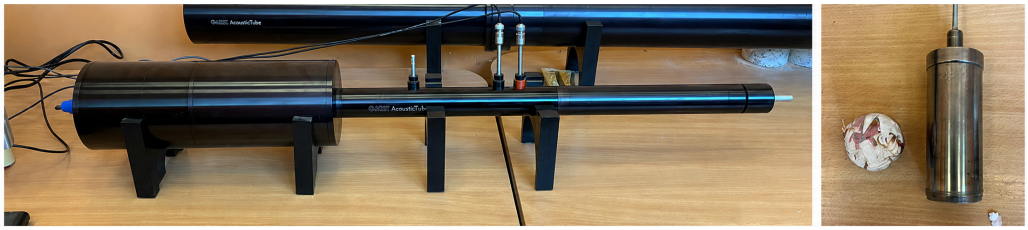


Figure 10. AFD 1000 impedance tube with a circular linen sample (40 mm in diameter) prepared using a cutting blade.

Sound absorption tests were performed using an AFD 1000 impedance tube (SINUS Messtechnik GmbH, Leipzig, Germany) (see Figure 10) to evaluate the acoustic behavior of the prepared specimens. During each measurement, the specimen was carefully positioned inside the tube to ensure full contact with the tube walls and minimize potential air leakage. The data acquisition and analysis software (SINUS Messtechnik GmbH, Leipzig, Germany) generated sound absorption coefficients at 6.25 Hz intervals across a recorded frequency vector from 6.25 to 6393.75 Hz. However, values outside the validated operating range of the impedance tube configuration were excluded, and only data from 100 to 4000 Hz were used for graphical presentation, statistical analysis, and interpretation. For each material type, measurements were obtained from three specimens, and the mean values were calculated. In the experimental setup, the AFD 1000 generated sound waves inside the tube, while two microphones detected the resulting sound-pressure signals. The collected signals were processed using the transfer-function method to calculate the normal-incidence sound absorption coefficient at each frequency (see Equations (4) and (5)).

The distinction between the recorded and analyzed frequency ranges was based on the geometrical and technical limitations of the AFD 1000 impedance tube. The tube had an internal diameter of 40 mm and was operated using two microphone configurations. A microphone spacing of 175 mm provided a usable frequency range of 100–900 Hz, whereas a microphone spacing of 35 mm provided a usable frequency range of 400–4000 Hz. The corresponding distances between the sample surface and the microphone closest to the sound source were 225 and 85 mm, respectively. The overlapping usable ranges of the two configurations enabled continuous analysis from 100 to 4000 Hz. The system was equipped with ¼-inch Class 1 microphones with a frequency response of 20 Hz–20 kHz, while the data acquisition system provided four simultaneously sampled analogue input channels at a sampling rate of 102.4 kHz. Although the software output contained frequency points below 100 Hz and above 4000 Hz, these values were not included in the analysis because they were outside the validated operating range of the applied tube and microphone configurations. Thus, the analyzed frequency range was determined by the tube diameter and microphone spacing rather than by the frequency response of the microphones or the sampling capability of the data acquisition system [38,39].

The acoustic measurements were conducted following the principles of ISO 10534-2 [38], which specifies the transfer-function method for determining normal-incidence sound absorption coefficients using an impedance tube. Prior to testing, the measurement system was calibrated according to the manufacturer's instructions. All specimens were conditioned under laboratory conditions (20 ± 2 °C; relative humidity 50 ± 5%) for at least 24 h before testing.

Calculation of the Sound Absorption Coefficient

The data obtained from the microphones were used to calculate the reflection coefficient [38,40]:

$$r(f) = \frac{H_{12}(f) - e^{-jkd}}{e^{jkd} - H_{12}(f)} \quad (4)$$

where

$H_{12}(f)$—measured transfer function between the microphones;
j—imaginary unit;
d—distance between microphone positions;
$k = 2\pi f/c$—wave number;
f—frequency;
c—speed of sound in air.

The sound absorption coefficient was calculated from the reflection coefficient [38,40]:

$$\propto (f) = 1 - [r(f)]^2 \quad (5)$$

where

$r(f)$—reflection coefficient.

Since the measurement equipment software includes a built-in function for automatic calculation of absorption coefficients, these calculations were not performed manually.

4.5. Data Processing and Analysis

In this study, data analysis was carried out using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA), complemented with the XLSTAT extension (version 2016.07.40563; Addinsoft, Paris, France). The software was used to organize the dataset, calculate descriptive statistics, and perform comparisons between material groups. Sound absorption coefficients were recorded at 6.25 Hz intervals for three replicate specimens of each material. The data were analyzed separately in three frequency ranges: 100–250 Hz,

250–1000 Hz, and 1000–4000 Hz, containing 25, 121, and 481 frequency points per specimen, respectively. For each replicate specimen, the mean absorption coefficient within each frequency range was calculated as the unweighted arithmetic mean of all discrete absorption coefficient values recorded within that range. No frequency weighting was applied. Individual frequency-point values were not treated as independent observations in the statistical comparisons. Instead, the statistical analysis was based on the three specimen-level frequency-averaged values obtained for each material. Consequently, each one-way ANOVA included five material groups, three observations per group ($n = 3$), and 15 observations in total. Separate one-way analyses of variance (ANOVA) were performed for the low-, mid-, and high-frequency ranges to determine whether statistically significant differences existed among the five textile materials. A p-value below 0.05 was considered statistically significant [41–43]. When a statistically significant ANOVA result was obtained, Tukey's HSD post hoc test was used to identify significant pairwise differences between material types [44,45].

The statistical outcomes were further supported with visual representations in the form of box plots, illustrating the distribution of absorption coefficients for each textile type. These diagrams highlight the median, quartiles, mean value, and overall data spread, thus providing insight into the distributional characteristics and symmetry of the results [46]. The graphical outputs served as an essential complement in interpreting the results across the different frequency ranges. The data analysis also incorporated the sound absorption coefficients of mineral wool and rock wool. The coefficients for rock wool were obtained from Rockwool Ltd. (Singapore), whereas the values for mineral wool were sourced from the publication by Jan Sikora and Jadwiga Turkiewicz [47,48].

Prior to ANOVA, the normality of the model residuals was assessed using the Shapiro–Wilk test, while the homogeneity of variances among material groups was evaluated using Levene's test. The Shapiro–Wilk test indicated no statistically significant deviations from normality in the low- ($p = 0.742$), mid- ($p = 0.402$), or high-frequency range ($p = 0.444$). Levene's test also indicated no statistically significant heterogeneity of variances in the low- ($p = 0.303$), mid- ($p = 0.051$), or high-frequency range ($p = 0.357$). Therefore, the assumptions of normality and homogeneity of variances were considered adequately satisfied. Statistical significance was accepted at $p < 0.05$.

5. Conclusions

1. Sound-absorbing materials produced from textile waste demonstrated strong acoustic potential, particularly in the mid-frequency range of 250–1000 Hz and the high-frequency range of 1000–4000 Hz, where several tested materials achieved mean absorption coefficients above 0.7.
2. One-way ANOVA and Tukey's HSD post hoc analysis confirmed statistically significant differences between textile types in the mid- and high-frequency ranges. Cotton showed the highest mean absorption coefficient in the mid-frequency range, while polyester and wool demonstrated the strongest performance at high frequencies. No statistically significant differences between fiber types were observed in the low-frequency range.
3. The study highlights that textile waste can be transformed into value-added products. The developed sound-absorbing panels could be applied as functional and aesthetic finishing materials. This approach aligns with circular economy principles, promotes resource reuse, and reduces the demand for virgin raw materials, while also delivering socio-economic and environmental benefits such as lower waste volumes and reduced emissions.

4. The comparative analysis of fiber-specific performance provides a basis for targeted material selection, enabling the optimization of acoustic panel design for different applications. This highlights the importance of integrating material characterization with product development to achieve both technical efficiency and sustainability.

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