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Research Paper

Development of Sustainable Lightweight Acoustic Composites from Denim, Flax, and Hemp Fibers

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The textile and clothing industries pose a serious problem in terms of environmental sustainability as they are among the sectors that produce the large amounts of waste worldwide. In this context, recycling both pre-consumer and post-consumer clothing waste into composite materials is of great importance in terms of both waste management and materials science. In this study, composite panels were developed using waste denim fabrics with different natural fiber compositions, recycled flax fibers derived from waste linen fabrics, and virgin hemp fibers as reinforcement materials. Polypropylene (PP)/polyethylene (PE) nonwoven interlining waste served as the matrix material, and the panels were fabricated by hot pressing at two different reinforcement-to-matrix ratios. The acoustic properties were evaluated through measurements of the sound absorption coefficient (SAC), noise reduction coefficient (NRC), and sound transmission loss (STL). In the case of denim waste, the results showed that flax- or hemp-blended samples provided better sound absorption than 100 % cotton samples, especially at a low matrix ratio. For the rest, while pure flax samples absorbed sound well, pure hemp samples showed good sound barrier properties with high STL.

Keywords: recycling, denim waste, hemp, flax, linen fabric, cotton, composite, sound absorption, sound insulation.

Notations

NFC – natural fiber composite,
NRC – noise reduction coefficient,
PE – polyethylene,
PLA – polylactic acid,
PP – polypropylene,
SAC – sound absorption coefficient,
STL – sound transmission loss.

1. Introduction

Environmental concerns and awareness have led to the use of natural fibers in composite materials to achieve sustainability in several industrial applications. Although synthetic fibers meet the requirements of many applications due to their higher tensile strength, natural fibers possess higher specific tensile strength due to their low density, making them competitive candidates (Lambrache, 2022). In addition to their environmentally friendliness, light weight, high specific strength, and in most cases, low cost, natural fibers also have advantages such as low thermal conductivity and high sound absorption. Due to these features, they are intensively used as reinforcement in construction, building, and insulation materials (Pichardo *et al.*, 2018; Ahmad *et al.*, 2015; Takagi, 2019).

The use of natural fibers as reinforcement material in composites developed for noise control, which is important for human health and comfort, has drawn the attention of many researchers seeking to develop sustainable and environmentally friendly materials alternative to silica-based and petroleum-based materials such as glass fiber, rock wool, mineral wool, and expanded polystyrene, which are commonly used in acoustic applications (Hassani *et al.*, 2021). By using natural fibers such as jute, ramie, flax, kenaf, coir, abaca, cabuya, totora and palm fiber, lightweight composite materials with satisfactory acoustic properties were obtained (Hassan *et al.*, 2021; Pawar *et al.*, 2022; Das *et al.*, 2022; Majumder *et al.*, 2023; Bravo-Moncayo *et al.*, 2024).

Natural fiber composite (NFC) used in acoustic and other applications can be produced from virgin fibers as well as waste and recycled fibers, further supporting sustainability. Therefore, the promising results obtained in the development of NFCs for acoustic applications encouraged researchers to investigate the acoustic characteristics of waste fiber-reinforced composites. In the literature, there are studies using recycled natural fibers, cotton fly, coconut/coir husk, sugarcane waste, industrial banana fiber waste, and industrial waste tea fiber as reinforcing materials in the development of composites for acoustic applications (Ersoy, Küçük, 2009; Putra *et al.*, 2013; Othmani *et al.*, 2016; Prabhu *et al.*, 2019; Hassan *et al.*, 2020; Gokulkumar *et al.*, 2021; Santoni *et al.*, 2021; Mondal *et al.*, 2022).

In these studies, fibers obtained from plant wastes found in certain geographical regions were generally used. In other words, agrowastes that are generally disposed of through throwing away, in situ burning, and composting were used. In some of these studies, hybrid reinforcement materials were used, including synthetic fibers such as E-glass, were used in the developed composites (Prabhu *et al.*, 2019; Gokulkumar *et al.*, 2021). As matrix materials, thermoset epoxy resin, polyurethane and polyester binder, and urea formaldehyde/ammonium chloride were used.

On the other hand, population growth and the corresponding increase in production increased the amount of waste generated in the textile and apparel industry, making it a critical issue (Sezgin *et al.*, 2021). Thus, in addition to agrowaste, it is important to investigate the use of wastes from textile products made of natural fibers in this field. Textile waste can be classified as production, pre-consumer, and post-consumer waste (Yalcin-Enis *et al.*, 2019). Recycling and reusing the waste generated in all these stages not only lessen the amount of waste but also reduce the burden on the environment. Because of the need to address global challenges in terms of sustainability and promotion of circular textile and fashion systems, the adoption of recycling and reuse of textile waste that replaces virgin fibers in the production of textiles, garments, accessories, and textile-reinforced composite materials has become more important (Pichardo *et al.*, 2018). According to 2023 data, the global production volume of virgin cotton fiber and other plant-based fibers was 24.4 million tons and 6.7 million tons, respectively. Cotton and non-cotton plant-based fibers accounted for about 29 % of the total global fiber production volume in 2023; however, the market share of recycled cotton was estimated at around 1 % of total cotton production. On the other hand, the share of recycled fibers is expected to grow significantly in the coming years to achieve a significant reduction in environmental pollution (Textile Exchange, 2024). For this to happen, new ideas, research, and development are needed for the use of waste and recycled materials from design to end use. At this context, transforming textile and clothing wastes into composite materials is an effective strategy to reduce environmental impacts and recycle industrial waste.

In the last few years, studies have been conducted for evaluating the acoustic and/or other insulation properties of composites reinforced with natural fibers sourced from apparel production or post-consumer waste. Among these, denim fabric waste, particularly 100 % cotton denim widely used in the fashion industry, has been extensively utilized. Recycled cotton denim fibers have been used as reinforcement in composite panels produced via hot pressing, with polypropylene (PP) fibers, ground PP derived from food and cleaning containers, and polyethylene (PE) granules obtained from bottle caps serving as matrix materials (Sezgin *et al.*, 2021; Kucukali-Ozturk *et al.*, 2022; Oztemur *et al.*, 2023). Similarly, Mago *et al.* (2024) used hydraulic compression molding to produce panels reinforced with denim shoddy and matrixed with recycled PP from cosmetic containers. Raj *et al.* (2020) investigated recycled denim shoddy and waste jute fibers as sustainable sound-absorbing materials, demonstrating that both exhibit comparable or superior acoustic performance to glass wool, with denim shoddy achieving up to tenfold and jute fiber up to fivefold cost advantages. Islam *et al.* (2022) used 100 % recycled cotton denim with Sorona or polylactic acid (PLA) binder fibers to develop acoustic insulation panels, while Hassani *et al.* (2021) created phenolic resin-bonded composites using an air-laid nonwoven processes. Although denim is primarily made from cotton, blends with other fibers such as elastane (for comfort) and polyester (for durability and cost reduction) are also common. Juciene *et al.* (2022) produced interior panels using cotton/PES denim waste and confirmed the potential of textile waste as the main component in acoustic applications.

Recent sustainability trends have also led to the inclusion of plant-based fibers like hemp and flax in denim fabrics. While most studies have focused on 100 % cotton denim or undefined 'denim shoddy,' there is limited information on the effect of fiber composition. However, evaluating the performance of NFCs made from denim waste of varied fiber contents is crucial for a sustainable design approach within the textile value chain. Therefore, this present study aims to develop 100 % recycled composite panels using denim waste containing different natural fibers: cotton, hemp, and flax, as reinforcement, and nonwoven interlining waste as the matrix. Since flax and hemp fibers are generally used in denim fabrics at low proportions, recycled flax fibers obtained from waste linen fabrics and virgin hemp fibers were also employed in this study in order to achieve higher blend ratios and to allow direct comparison with pure flax and pure hemp composites. Two different reinforcement-to-matrix ratios were used in the production of composite panels, their acoustic performance was tested, and their potential use in buildings and vehicles as insulation materials was evaluated. Investigating recycling alternatives for denim, a timeless fashion product, particularly with diverse natural fiber compositions, is expected to offer valuable contributions to sustainability.

2. Experimental part

2.1. Materials

Fabric wastes made of natural fibers were used as fiber reinforcement material in the composite panels. Cotton fiber was obtained from waste denim fabric, and flax fiber was obtained from waste linen fabric. Hemp fiber was supplied in virgin form by Karacasu Tekstil. These fibers were used in the production of composite panels containing pure fibers and 50/50 blends. In addition, 80/20 cotton/flax, and 80/20 cotton/hemp blends were obtained from waste denim fabrics. PP/PE (80/20) spunbonded nonwoven interlining waste was used as the matrix material in the composite panels. Figure 1 shows the fibers and matrix material used in the study. The areal density of the nonwoven interlining was measured to be approximately 20 g/m^2. The average densities of cotton, flax, hemp, PP, and PE fibers were approximated in accordance with the literature (Lu *et al.*, 2012; Yan *et al.*, 2014; Rohen *et al.*, 2017; Unterweger, 2014; Çolakoğlu, 2006).

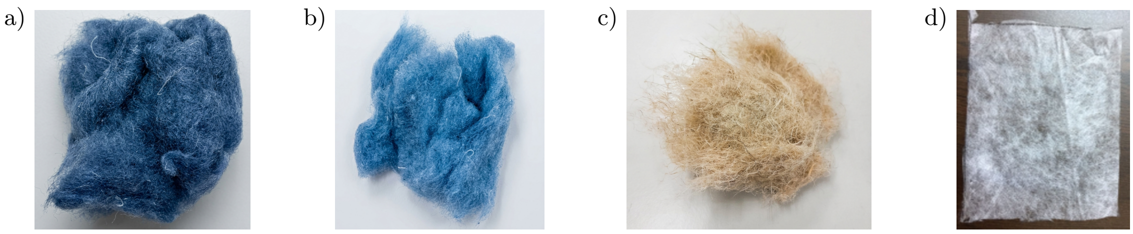


Fig. 1. Fibers and matrix material: a) cotton, b) flax, c) hemp, d) PP/PE nonwoven.

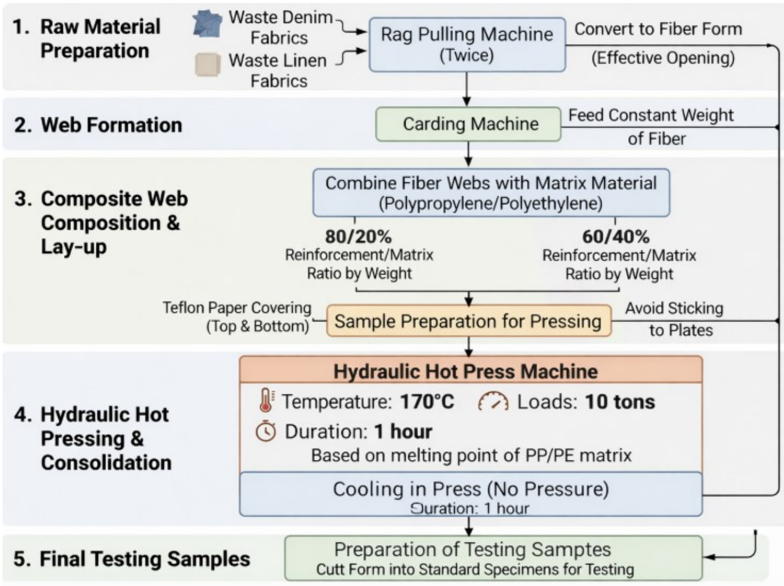
The characteristics of the materials used in the experiments are shown in Table 1. Due to the mechanical recycling process (rag pulling), the fibers exhibited a non-uniform length distribution. The length of the hemp fibers was reported as approximately 36 mm according to the supplier's specifications.

Table 1. Characteristics of the materials used.

Material type	Source	Fiber type	Form	Density [g/cmł]
Waste denim fabric	Post-consumer textile waste	Cotton	Recycled (mechanically opened)	~1.51
Waste linen fabric	Post-consumer textile waste	Flax	Recycled (mechanically opened)	~1.50
Hemp fiber	Karacasu Tekstil (Türkiye)	Hemp	Virgin	~1.40
PP/PE spunbonded nonwoven	Industrial interlining waste	PP/PE (80/20)	Nonwoven	~0.91–0.97

2.2. Production of composite panels

Waste denim fabrics and waste linen fabric were converted into fiber form by using a rag-pulling machine twice for effective opening. The fibers were then transferred to a carding machine to obtain fiber webs by feeding a constant mass of fibers. The fiber webs were then combined with the matrix material at reinforcement-to-matrix ratios of 80 %/20 % and 60 %/40 %. A series of composite panels were produced by a hydraulic hot press machine. The webs were placed on the bottom plate of hot press machine, with Teflon paper covering the bottom and top surfaces of the samples to prevent the sticking of matrix material onto the plates. The composite panels were pressed at 170 °C, based on the melting temperature of the PP/PE matrix material, for 1 h under a load of 10 tons. The samples were then cooled for 1 h in the press without applying pressure. The production steps of the composite panels are presented in Fig. 2.



a)  b)  c)  d) 

Fig. 2. Production steps of the composite panels: a) recycled fibers, b) carding process, c) samples for hot pressing, d) preparation of test samples.

2.3. Testing methods

The thickness of the composite panels was measured using a digital caliper. Areal densities were calculated by dividing the measured mass [g] by the measured area of the sample [cm^2]. To calculate the bulk density, the areal density was divided by the sample thickness [cm]. The porosity of the samples was calculated according to ASTM D2734-16 (2016) standard by using:

$$\text{Porosity}\ (\varPhi) = \frac{\rho ct - \rho e}{\rho ct} \times 100, \tag{1}$$

where ρ_{ct} is the theoretical density, and ρ_e is the experimental density (bulk density) of the composite panels. The theoretical density of the composite panels was calculated as the weighted average fiber density of the sample.

The tortuosity of the composite panels, which is the ratio of the actual flow path length to the straight distance between the ends of the flow path, was calculated by using the empirical formula based on porosity (Fatima, Mohanty, 2011):

$$\text{Tortuosity}\,(\tau) = 1 + \frac{1-\Phi}{2\Phi}. \tag{2}$$

The sound absorption coefficient (SAC) and sound transmission loss (STL) of the samples were measured by an impedance tube (TestSENS acoustic performance measurement system) developed by BIAS Engineering (Türkiye) shown in Fig. 3. The impedance tube was selected because it allows measurements on small samples. Circular samples with a diameter of 29 mm were prepared, the sound absorption test was conducted according to ASTM E1050-19 (2019) standard using a two-microphone impedance measurement tube, whereas the STL test was conducted according to ASTM E2611-17 (2019) standard using a four-microphone impedance measurement tube at frequencies from 200 Hz to 6400 Hz at room temperature. Schematic diagrams of impedance tube with two microphones for SAC measurements, and with four microphones for STL measurements are shown in Fig. 4 and Fig. 5, respectively.

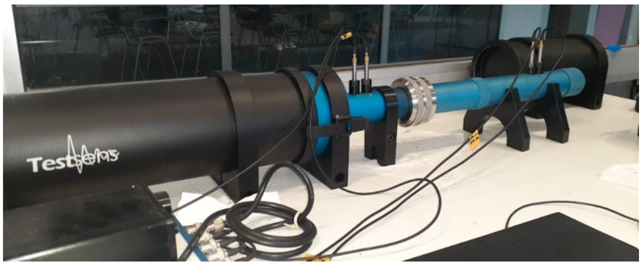


Fig. 3. Impedance tube used for SAC and STL measurements.

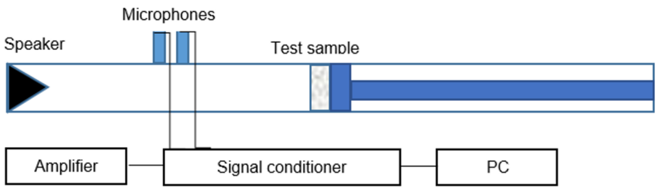


Fig. 4. Schematic diagram of the impedance tube with two microphones for SAC measurements.

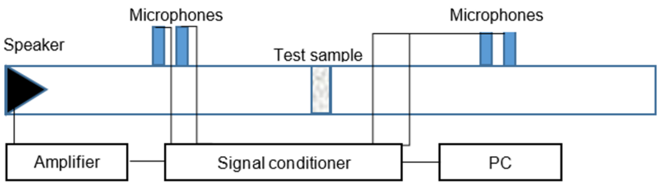


Fig. 5. Schematic diagram of the impedance tube with four microphones for STL measurements.

The SAC and STL of the samples were calculated by the measurement system according to the following equations:

$$\text{SAC}(\alpha) = \frac{\text{energy of sound absorbed by the surface}}{\text{total sound energy incident on the surface}}, \tag{3}$$

$$\text{STL}\,(\text{db}) = 10 \log 10 \frac{\text{power of the incident wave energy}}{\text{power of the transmitted wave energy}}. \tag{4}$$

The noise reduction coefficient (NRC), which enables the absorption performance to be expressed as a single quantitative value, was calculated as the arithmetic mean of the SAC values at frequencies of (250, 500, 1000, 2000, 3000, and 3500) Hz (see Eq. (5)). It corresponds to the ability of a material to absorb broad-spectrum sound, and since textile materials are porous absorbers and provide higher sound absorption at medium to high frequencies, the SAC values at 3000 Hz and 3500 Hz were included in the calculation of NRC (Lou *et al.*, 2005;

Hassanzadeh *et al.*, 2014; Selver, 2019; Sağlam *et al.*, 2022). The calculated NRC values were rounded to the nearest 0.05 according to ASTM C423-17 (2017) standard:

$$\text{NRC} = \frac{\alpha 250 + \alpha 500 + \alpha 1000 + \alpha 2000 + \alpha 3000 + \alpha 3500}{6}. \tag{5}$$

3. Results and discussion

The physical properties of the composite samples produced with different fiber and matrix ratios are shown in Table 2. In particular, the 100 % hemp panels exhibited the highest bulk density and the lowest porosity values, while lower density and higher porosity were obtained for pure flax and flax-blended samples. Notably, the thinnest panels were those composed entirely of hemp.

Table 2. Characteristics of the composite panels.

Sample code	Composition	Fiber ratio	Matrix ratio	Sample thickness [mm]	Sample weight [g]	Areal density [g/cm^2]	Bulk density [g/cm^3]	Weighted average density [g/cm^3]	Porosity (Φ)	Tortuosity (τ)
Cotton_20	100 % cotton	80	20	4.34	1.674	0.254	0.584	1.975	0.704	1.104
Flax_20	100 % flax			5.56	1.407	0.213	0.383	1.967	0.805	1.078
Hemp_20	100 % hemp			3.90	2.309	0.350	0.897	1.887	0.525	1.125
50Co50Flax_20	50 % cotton/ 50 % flax			5.12	1.202	0.182	0.356	1.971	0.820	1.074
50Co50Hemp_20	50 % cotton/ 50 % hemp			4.74	1.392	0.211	0.445	1.931	0.770	1.089
50Hemp50Flax_20	50 % hemp/ 50 % flax			4.58	1.343	0.203	0.444	1.927	0.770	1.089
80Co20Flax_20	80 % cotton/ 20 % flax			5.48	1.181	0.179	0.326	1.973	0.835	1.069
80Co20Hemp_20	80 % cotton/ 20 % hemp			5.17	1.307	0.198	0.383	1.957	0.804	1.079
Cotton_40	100 % cotton	60	40	4.94	2.195	0.332	0.673	1.712	0.607	1.119
Flax_40	100 % flax			4.82	1.655	0.251	0.520	1.706	0.695	1.106
Hemp_40	100 % hemp			3.91	2.021	0.306	0.783	1.646	0.524	1.125
50Co50Flax_40	50 % cotton/ 50 % flax			5.23	1.968	0.298	0.570	1.709	0.666	1.111
50Co50Hemp_40	50 % cotton/ 50 % hemp			4.55	1.606	0.243	0.535	1.679	0.681	1.109
50Hemp50Flax_40	50 % hemp/ 50 % flax			5.28	1.890	0.286	0.542	1.676	0.676	1.109
80Co20Flax_40	80 % cotton/ 20 % flax			5.37	1.607	0.243	0.453	1.710	0.735	1.097
80Co20Hemp_40	80 % cotton/ 20 % hemp			5.65	1.730	0.262	0.464	1.698	0.727	1.099

In the present study, hemp fiber was used in its virgin raw fiber form in the pure hemp and 50/50 blended composites. This means it was not recycled from fabrics that had undergone some finishing treatments. The intrinsic stiffness of natural fibers plays a decisive role in determining the porosity of the resulting composites. As fiber stiffness increases, the fiber elastic recovery ability decreases and they deform less when compressed by the matrix, which results in higher composite density and lower porosity. Fibers with a high elastic modulus, such as hemp (~23.5 GPa to 90 GPa), form more rigid and compact reinforcement networks, which facilitates closer fiber packing and consequently leads to lower porosity levels in the composite. In contrast, cotton fibers, with a significantly lower stiffness (~5.5 GPa to 12.6 GPa), are more flexible and deformable, often resulting in irregular packing and higher porosity. Although flax fibers also have a high stiffness (~27.6 GPa to 103 GPa), comparable to that of hemp, the flax fibers used in the pure flax and 50/50 blended composites were recycled from fabric. Due to the chemical treatments in textile processing, their stiffness had decreased. This resulted in higher porosity and lower bulk density in these samples (Yan *et al.*, 2014).

Significant differences were generally observed in thickness, density, and porosity values between the samples containing 80 % and 60 % fiber. While lower bulk density and higher porosity were observed in the 80 % fiber samples, bulk density increased and porosity decreased, increasing the matrix amount in the 60 % fiber samples. In addition, the tortuosity values increased slightly with increasing matrix content and varied between 1.07 and 1.12.

Table 3 provides the first SAC peak for each sample, along with the corresponding frequency. It also indicates the frequency range over which the SAC exceeded 0.5 – a value commonly considered the threshold for effective sound absorption (Khair *et al.*, 2016). The SAC curves of the samples are shown in Fig. 6, Fig. 7, and Fig. 8 over the frequency range from 200 Hz to 6400 Hz.

Table 3. Maximum SAC values of the composite panels.

Sample code	Frequency range [Hz] of $\alpha > 0.5$	First peak SAC (α)	First peak SAC frequency [Hz]
Cotton_20	–	0.418	5054
Flax_20	1382–6400	0.531	1674
Hemp_20	–	0.227	4330
50Co50Flax_20	1684–6400	0.726	4636
50Co50Hemp_20	1740–6400	0.722	2916
50Hemp50Flax_20	2306–6400	0.569	5686
80Co20Flax_20	1716–6400	0.577	2158
80Co20Hemp_20	1570–6400	0.569	1764
Cotton_40	–	0.346	3112
Flax_40	1440–6400	0.693	2336
Hemp_40	–	0.171	5752
50Co50Flax_40	3604–6400	0.735	5886
50Co50Hemp_40	2806–6400	0.635	2712
50Hemp50Flax_40	3366–6400	0.542	5146
80Co20Flax_40	2004–6400	0.501	2848
80Co20Hemp_40	2006–6400	0.633	2694

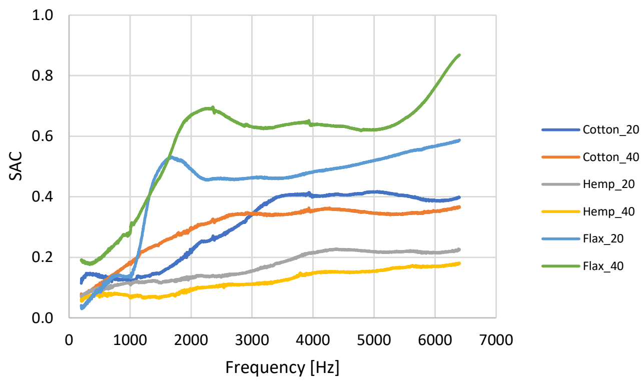


Fig. 6. SAC of pure cotton, flax, and hemp fiber-reinforced composites.

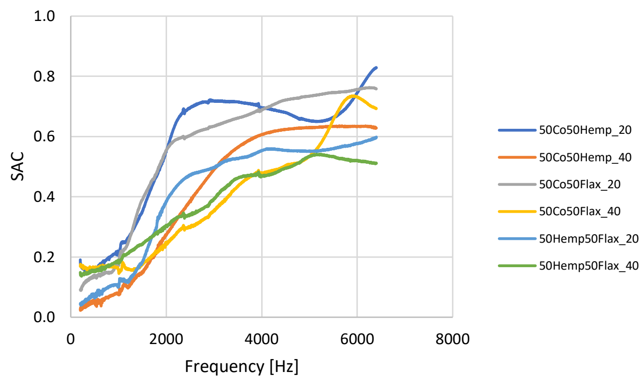


Fig. 7. SAC of 50/50 cotton, flax, and hemp blended fiber-reinforced composites.

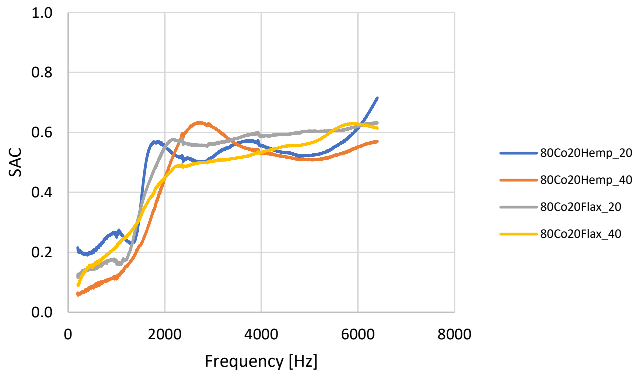


Fig. 8. SAC of 80/20 cotton, flax, and hemp blended fiber-reinforced composites.

The results highlight that the sound absorption performance of the composite panels was found to be strongly dependent on both the fiber type and the matrix ratio. Among the pure fiber composites, the flax panels exhibited the highest performance, with Flax_20 achieving a maximum SAC of 0.531 and Flax_40 reaching 0.693. Pure cotton panels showed moderate performance, while pure hemp panels displayed the lowest values, particularly when the matrix ratio was increased from 20 % to 40 %, where the maximum SAC decreased from 0.227 to 0.171. The reason for this was the fact that these panels were the thinnest and had the lowest porosity, as mentioned before. Regarding the fiber type, pure flax samples, and in terms of matrix ratio, samples with a low matrix content exhibited SAC values exceeding 0.5 across a broader frequency range.

In the 50/50 blended samples, the combination of cotton with flax or hemp considerably improved sound absorption compared with pure cotton, with 50Co50Flax_20 and 50Co50Hemp_20 achieving maximum SAC values of 0.726 and 0.722, respectively. Lower peak SAC values were obtained for the 80/20 blended composites; however, the peak values were recorded at lower frequencies, especially in the samples with higher fiber content. In general, lower SAC values were recorded at higher matrix ratios, which was expected due to the decreased porosity.

Table 4 presents the SAC values of the composite panels between 250 Hz and 3500 Hz together with the corresponding NRC values. The 100 % flax composites (Flax_20 and Flax_40) and the 50Co50Hemp_20, 50Co50Flax_20, and 80Co20Hemp_20 blended samples exhibited better sound absorption performance, with NRC values reaching 0.40–0.45. In contrast, the NRC values of 100% cotton and 100 % hemp samples remained quite low (0.10–0.25). The fiber-to-matrix ratio was also an important factor, and the samples containing 60 % fiber generally exhibited lower SACs, with performance weakening particularly at mid-frequencies (1000 Hz to 2000 Hz). An NRC of 0.40 or higher indicates effective sound absorption, while values above 0.20 classify a material as acoustic. Higher NRC values reflect better absorption (Samuel *et al.*, 2023). In this context, all samples except the pure hemp ones can be classified as acoustic materials; however, the Flax_20, Flax_40, 50Co50Hemp_ 20, 50Co50Flax_20, and 80Co20Hemp_20 samples, in particular, may be regarded as effective sound-absorbing materials.

Table 5 shows the STL values of the composite panels with different fiber compositions and matrix ratios across the frequency range between 250 Hz and 6300 Hz. The corresponding STL graphs as a function of frequency are shown in Fig. 9, Fig. 10, and Fig. 11.

All samples displayed a gradual increase in transmission loss with rising frequency, particularly above 4000 Hz, confirming the enhanced barrier effect of these composites at higher frequencies. Pure hemp samples exhibited the highest STL values for both matrix ratios. This can be attributed mainly to the high bulk densities of these samples. According to the mass law, as the mass per unit area of a material increases, STL rises logarithmically. Since bulk density contributes directly to the mass of the material, an increase in bulk density generally leads to higher STL values (Arjunan *et al.*, 2021).

The STL results of the pure and blended fiber composites revealed a clear dependence on both the fiber type and the matrix ratio. For the pure fiber composites (Fig. 9), an increase in the matrix content from 20 % to 40 % generally improved the STL values, in agreement with previous findings in the literature (Sezgin *et al.*, 2022).

TABLE 4. SACs of the composite panels in the range from 250 Hz to 3500 Hz with the corresponding NRC values.

Sample code	SAC						NRC
	250 Hz	500 Hz	1000 Hz	2000 Hz	3000 Hz	3500 Hz	
Cotton_20	0.133	0.134	0.125	0.217	0.343	0.403	0.25
Flax_20	0.040	0.084	0.133	0.491	0.463	0.462	0.30
Hemp_20	0.077	0.089	0.112	0.131	0.154	0.185	0.10
50Co50Flax_20	0.103	0.135	0.179	0.554	0.634	0.661	0.40
50Co50Hemp_20	0.161	0.154	0.212	0.549	0.718	0.715	0.40
50Hemp50Flax_20	0.047	0.063	0.103	0.386	0.498	0.528	0.25
80Co20Flax_20	0.129	0.142	0.170	0.547	0.562	0.581	0.35
80Co20Hemp_20	0.200	0.203	0.258	0.552	0.518	0.564	0.40
Cotton_40	0.076	0.105	0.181	0.292	0.343	0.340	0.20
Flax_40	0.183	0.192	0.281	0.668	0.631	0.636	0.45
Hemp_40	0.064	0.068	0.068	0.090	0.111	0.124	0.10
50Co50Flax_40	0.168	0.158	0.158	0.240	0.353	0.435	0.25
50Co50Hemp_40	0.032	0.044	0.076	0.274	0.491	0.565	0.25
50Hemp50Flax_40	0.140	0.156	0.188	0.301	0.392	0.461	0.25
80Co20Flax_40	0.108	0.150	0.217	0.448	0.504	0.515	0.30
80Co20Hemp_40	0.061	0.084	0.117	0.444	0.617	0.560	0.30

TABLE 5. STL values of the composite panels at different frequencies.

Sample code	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz	6300 Hz
Cotton_20	5.22	4.29	5.64	5.53	6.78	7.03	7.21	9.54	11.00	12.46	13.87	15.35	17.47	19.68	22.72
Flax_20	6.86	7.45	8.18	8.99	9.98	11.32	10.99	9.67	11.41	13.68	15.97	18.06	21.86	24.52	27.11
Hemp_20	17.77	16.95	17.76	17.84	18.57	19.10	19.44	21.21	22.15	22.75	22.05	23.18	25.12	26.55	29.35
50Co50Flax_20	4.88	4.59	5.46	5.75	6.34	7.32	6.04	7.95	9.50	11.11	12.52	14.61	16.57	17.89	19.30
50Co50Hemp_20	4.33	3.53	5.07	5.02	6.55	4.58	4.61	5.66	9.87	9.72	11.47	15.60	12.96	15.54	20.31
50Hemp50Flax_20	14.45	14.81	15.27	15.72	16.16	16.66	17.56	17.62	14.02	15.73	17.59	18.78	19.55	21.49	23.63
80Co20Flax_20	6.40	5.41	6.82	6.96	8.34	9.01	4.91	8.31	9.80	10.94	12.18	13.10	14.92	17.09	18.63
80Co20Hemp_20	13.00	11.38	12.48	12.45	13.43	13.35	8.09	11.44	13.31	15.15	16.12	17.19	20.51	22.61	26.21
Cotton_40	10.48	9.20	10.56	10.55	11.65	11.99	11.33	13.83	14.66	14.98	16.30	17.86	20.09	22.57	24.69
Flax_40	4.63	3.71	4.91	5.00	6.06	5.33	4.27	7.07	8.13	9.27	11.08	13.07	15.45	17.44	20.99
Hemp_40	32.36	31.25	31.93	31.39	33.40	33.33	33.38	33.09	33.98	34.61	35.49	34.31	32.68	31.80	34.84
50Co50Flax_40	28.94	26.63	27.33	27.02	27.22	27.56	26.71	26.74	27.05	26.81	27.86	27.22	26.15	28.70	35.96
50Co50Hemp_40	18.58	18.68	18.77	18.84	18.82	18.97	19.28	19.24	19.29	19.69	19.99	19.83	19.16	20.23	21.91
50Hemp50Flax_40	13.09	11.49	12.71	12.54	13.55	13.94	12.88	14.82	14.87	14.88	16.07	17.16	17.98	19.32	21.66
80Co20Flax_40	13.94	13.30	14.08	14.20	14.94	15.17	14.87	15.99	15.68	15.85	16.70	17.85	19.31	21.07	24.25
80Co20Hemp_40	5.54	4.12	5.27	5.28	6.40	6.62	6.37	8.76	10.07	11.20	12.20	13.69	15.69	18.02	20.57

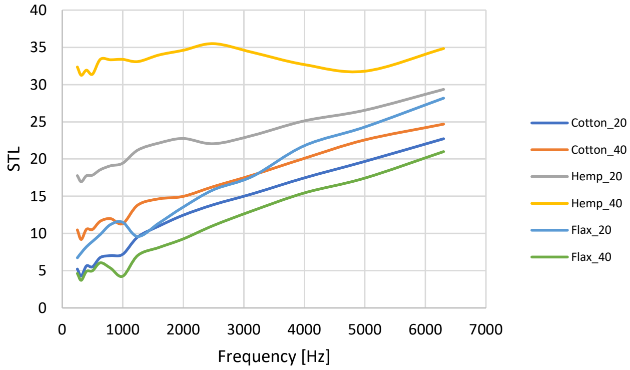


Fig. 9. STL of pure cotton, flax, and hemp fiber-reinforced composites.

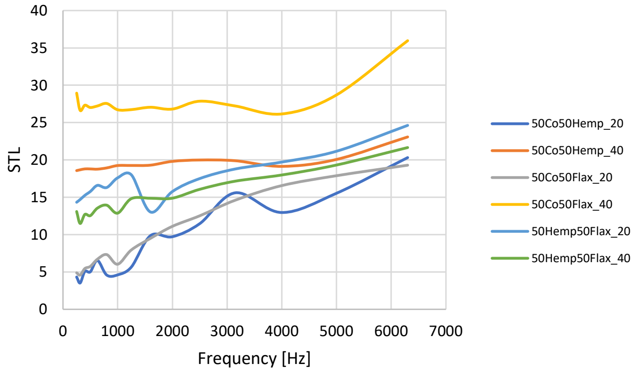


Fig. 10. STL of 50/50 cotton, flax, and hemp blended fiber-reinforced composites.

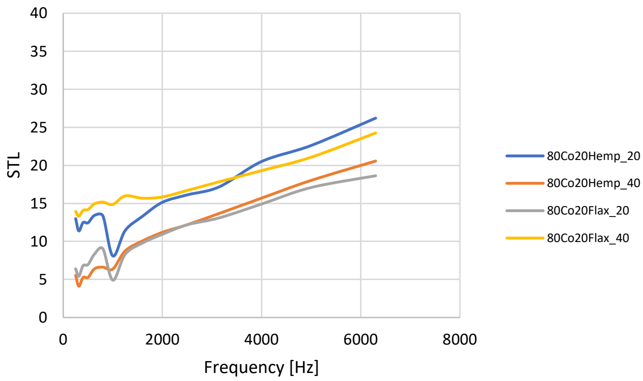


Fig. 11. STL of 80/20 cotton, flax, and hemp blended fiber-reinforced composites.

This effect was most pronounced in the hemp-based samples, where Hemp_40 consistently exhibited the highest STL across the tested frequency range, followed by the cotton- and flax-based composites. This can be attributed to the higher bulk density of the hemp fiber composites, contributing to improved STL (Berardi, Iannace, 2015).

For the 50/50 blended composites (Fig. 10), the positive influence of the higher matrix ratio was also evident. In particular, 50Co50Flax_40 showed superior STL performance compared with the other blends. However, the 80/20 blended composites (Fig. 11) demonstrated a different trend. The 80Co20Hemp_20 sample outperformed its 40 % counterpart, while 80Co20Flax_40 yielded higher STL values than its 20 % counterpart. Nevertheless, the overall STL levels of the 80/20 blends were generally lower compared to those of the pure fiber and 50/50 blended composites, suggesting that higher cotton content diminishes the acoustic barrier efficiency of the composites. Furthermore, the surface roughness caused by cracks and cavities on the surface of flax and hemp fibers may have increased the friction between the fiber surface and the sound waves, causing an increase in the STL in these samples (Sezgin *et al.*, 2022).

4. Conclusion

The present study demonstrated that denim waste and recycled natural fibers can be effectively transformed into lightweight and sustainable acoustic composites, offering a viable alternative to conventional petroleum-based materials. The results clearly showed that both fiber type and reinforcement/matrix ratio significantly influence the acoustic performance.

Specifically, blended composites based on denim waste exhibited higher sound absorption coefficients and NRC values compared to the 100 % cotton samples, confirming the positive contribution of flax and hemp fibers. Flax-based composites showed strong sound absorption performance, whereas hemp-based panels provided superior STL due to their higher bulk density and more compact structure.

Increasing the reinforcement content (i.e., reducing the matrix ratio) improved the sound absorption performance by increasing porosity and enhancing the complexity of the sound propagation paths, thereby promoting viscous and thermal dissipation mechanisms.

In terms of practical applications, such as interior acoustic panels for buildings or vehicle cabins, composite blends containing 50 % cotton/50 % flax or 50 % cotton/50 % hemp with a low matrix ratio (20 %) are recommended. These configurations achieved a high NRC of 0.40, making them effective for broad-spectrum sound absorption. For applications requiring a sound barrier effect, such as wall partitions, 100 % hemp composites with a higher matrix ratio (40 %) are the most practical recommendation due to their STL and higher bulk density.

Beyond their acoustic performance, the use of pre- and post-consumer textile wastes contributes directly to environmental sustainability by diverting valuable resources from landfills and supporting circular economy principles. Although cotton remains the primary fiber used in denim production, growing sustainability concerns and evolving consumer expectations have encouraged the incorporation of flax and hemp into denim products. The results of this study indicate that these natural fiber blends not only perform well during use but also offer advantages in terms of end-of-life waste management. Consequently, these emerging trends support sustainability across production, consumption, and post-use phases.

Future research should focus on evaluating durability under varying environmental conditions to better understand long-term performance. In addition, although the fibers in the present study were distributed in a relatively random manner, future studies should investigate controlled fiber orientation and alignment, as these factors may significantly influence acoustic performance.

Moreover, the use of bio-based matrices such as PLA should be explored to develop fully biodegradable composites and further reduce environmental impact. Finally, the incorporation of suitable additives to enhance functional properties, such as moisture resistance and fire retardancy, should be investigated to improve the applicability of these composites in construction and automotive applications.

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Conflict of interests

The authors declare that there are no known competing financial interests or personal relationships that could have influenced the work described in this paper.

Authors' contributions

Nazan Okur: conceptualization, methodology, material procurement, data interpretation and analysis, and writing the original manuscript. Canan Saricam: conceptualization, material procurement and preparation, experimental testing. All authors reviewed and approved the final manuscript.

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References

1. Ahmad F., Choi H.S., Park M.K. (2015), A review: natural fiber composites selection in view of mechanical, light weight, and economic properties, *Macromolecular Materials and Engineering*, **300**(1): 10–24, https://doi.org/10.1002/mame.201400089.
2. Arjunan A., Baroutaji A., Latif A. (2021), Acoustic behaviour of 3D printed titanium perforated panels, *Results in Engineering*, **11**: 100252, https://doi.org/10.1016/j.rineng.2021.100252.
3. ASTM C423-17 (2017), *Standard test method for sound absorption and sound absorption coefficients by the reverberation room method*, ATM International.
4. ASTM D2734-16 (2016), *Standard test methods for void content of reinforced plastics*, ASTM International.
5. ASTM E1050-19 (2019), *Standard test method for impedance and absorption of acoustical materials using a tube, two microphones and a digital frequency analysis system*, ASTM International.
6. ASTM E2611-17 (2019), *Standard test method for normal incidence determination of porous material acoustical properties based on the transfer matrix method*, ASTM International.
7. Berardi U., Iannace G. (2015), Acoustic characterization of natural fibers for sound absorption applications, *Building and Environment*, **94**(Part 2): 840–852, https://doi.org/10.1016/j.buildenv.2015.05.029.
8. Bravo-Moncayo L., Argotti-Gómez M., Jara O., Puyana-Romero V., Ciaburro G., Guerrero V.H. (2024), Thermo-acoustic properties of four natural fibers, *Musa textilis*, *Furcraea andina*, *Cocos nucifera*, and *Schoenoplectus californicus*, for building applications, *Buildings*, **14**(8): 2265, https://doi.org/10.3390/buildings14082265.
9. Çolakoğlu M. (2006), Damping and vibration analysis of polyethylene fiber composite under varied temperature, *Turkish Journal of Engineering and Environmental Sciences*, **30**(6): 351–357.
10. Das P.P., Chaudhary V., Ahmad F., Manral A., Gupta S., Gupta P. (2022), Acoustic performance of natural fiber reinforced polymer composites: Influencing factors, future scope, challenges, and applications, *Polymer Composites*, **43**(3): 1221–1237, https://doi.org/10.1002/pc.26455.
11. Ersoy S., Küçük H. (2009), Investigation of industrial tea-leaf-fibre waste material for its sound absorption properties, *Applied Acoustics*, **70**(1): 215–220, https://doi.org/10.1016/j.apacoust.2007.12.005.
12. Fatima S., Mohanty A.R. (2011), Acoustical and fire-retardant properties of jute composite materials, *Applied Acoustics*, **72**(2–3): 108–114, https://doi.org/10.1016/j.apacoust.2010.10.005.
13. Gokulkumar S., Thyla P.R., Prabhu L., Sathish S. (2021), Characterization and comparative analysis on mechanical and acoustical properties of camellia sinensis/ananas comosus/glass fiber hybrid polymer composites, *Journal of Natural Fibers*, **18**(7): 978–994, https://doi.org/10.1080/15440478.2019.1675215.
14. Hassan T. *et al.* (2020), Acoustic, mechanical and thermal properties of green composites reinforced with natural fibers waste, *Polymers*, **12**(3): 654, https://doi.org/10.3390/polym12030654.
15. Hassan T. *et al.* (2021), Factors affecting acoustic properties of natural-fiber-based materials and composites: a review, *Textiles*, **1**(1): 55–85, https://doi.org/10.3390/textiles1010005.
16. Hassani P., Soltani P., Ghane M., Zarrebini M. (2021), Porous resin-bonded recycled denim composite as an efficient sound-absorbing material, *Applied Acoustics*, **173**: 107710, https://doi.org/10.1016/j.apacoust.2020.107710.
17. Hassanzadeh S., Hasani H., Zarrebini M. (2014), Analysis and prediction of the noise reduction coefficient of lightly-needled Estabragh/polypropylene nonwovens using simplex lattice design, *The Journal of The Textile Institute*, **105**(3): 256–263, https://doi.org/10.1080/00405000.2013.835903.
18. Islam S., El Messiry M., Sikdar P.P., Seylar J., Bhat G. (2022), Microstructure and performance characteristics of acoustic insulation materials from post-consumer recycled denim fabrics, *Journal of Industrial Textiles*, **51**(4_suppl): 6001S–6027S, https://doi.org/10.1177/1528083720940746.

19. Juciene M., Dobilaitė V., Albrektas D., Bliūdžius R. (2022), Investigation and evaluation of the performance of interior finishing panels made from denim textile waste, *Textile Research Journal*, **92**(23–24): 4666–4677, https://doi.org/10.1177/00405175221109636.

20. Khair F.A., Putra A., Nor M.J., Selamat M.Z. (2016), Analysis of sound absorption of hollow tube absorbers, *International Journal of Automotive and Mechanical Engineering*, **13**(2): 3492–3502, https://doi.org/10.15282/ijame.13.2.2016.16.0288.

21. Kucukali-Ozturk M., Yalçin Eniş I., Sezgin H. (2022), Development of 100% recycled thermoplastic composites for sound insulated acoustic panels, *Materials Science Forum*, **1053**: 352–357, https://doi.org/10.4028/p-q9e23m.

22. Lambrache N., Renagi O., Olaru L., N'Drelan B. (2022), Composite materials with natural fibers, [in:] *Fiber-Reinforced Plastics*, Masuelli M.A. [Ed.], https://doi.org/10.5772/intechopen.101818.

23. Lou C.-W., Lin J.-H., Su K.-H. (2005), Recycling polyester and polypropylene nonwoven selvages to produce functional sound absorption composites, *Textile Research Journal*, **75**(5): 390–394, https://doi.org/10.1177/0040517505054178.

24. Lu N., Swan R.H. Jr., Ferguson I. (2012), Composition, structure, and mechanical properties of hemp fiber reinforced composite with recycled high-density polyethylene matrix, *Journal of Composite Materials*, **46**(16): 1915–1924, https://doi.org/10.1177/0021998311427778.

25. Mago J., Jaish S., Negi A., Bolton J.S., Fatima S. (2024), Investigating the acoustic performance of sustainable composites utilizing recycled polypropylene and denim shoddy: fabrication, characterization, and theoretical modelling, [in:] *INTER-NOISE and NOISE-CON Congress and Conference Proceedings,* (7): 4017–4028, https://doi.org/10.3397/IN_2024_3403.

26. Majumder A., Achenza M., Mastino C.C., Baccoli R., Frattolillo A. (2023), Thermo-acoustic building insulation materials fabricated with recycled fibers – jute, wool and loofah, *Energy and Buildings*, **293**: 113211, https://doi.org/10.1016/j.enbuild.2023.113211.

27. Mondal M.S., Sarkar J., Hasan N., Mehedi H.A., Dutta P. (2022), Development of recycled natural fiber based composite material by hand lay-up process and analysis of its acoustic & physical properties, *Journal of Natural Fibers*, **19**(16): 14898–14908, https://doi.org/10.1080/15440478.2022.2069193.

28. Othmani C. *et al.* (2016), Experimental and theoretical investigation of the acoustic performance of sugarcane wastes based material, *Applied Acoustics*, **109**: 90–96, https://doi.org/10.1016/j.apacoust.2016.02.005.

29. Oztemur J., Ozdemir S., Sezgin H., Yalcin-Enis İ. (2023), Manufacturing sound absorption panel from textile waste: a design approach, [in:] *International Conference – Smart Textiles and Emerging Technologies*, **2**(1): 40–49, https://doi.org/10.61135/stet2024.

30. Pawar K.S., Bagha A.K., Bahl S., Nandan D. (2022), Significant applications of composite and natural materials for vibration and noise control: a review, *Advancement in Materials, Manufacturing and Energy Engineering*, **2**: 211–220, https://doi.org/10.1007/978-981-16-8341-1_17.

31. Pichardo P.P., Martínez-Barrera G., Martínez-López M., Ureña-Núñez F., Ávila-Córdoba L.I. (2018), Waste and recycled textiles as reinforcements of building materials, [in:], *Natural and Artificial Fiber Reinforced Composites as Renewable Sources*, Gururaja M.N. [Ed.], pp. 89–106, https://doi.org/10.5772/intechopen.70620.

32. Prabhu L., Krishnaraj V., Gokulkumar S., Sathish S., Ramesh M. (2019), Mechanical, chemical and acoustical behavior of sisal – tea waste – glass fiber reinforced epoxy based hybrid polymer composites, *Materials Today: Proceedings*, **16**(Part 2): 653–660, https://doi.org/10.1016/j.matpr.2019.05.142.

33. Putra A., Abdullah Y., Efendy H., Farid W.M., Ayob M.R., Py M.S. (2013), Utilizing sugarcane wasted fibers as a sustainable acoustic absorber, *Procedia Engineering*, **53**: 632–638, https://doi.org/10.1016/j.proeng.2013.02.081.

34. Raj M., Fatima S., Tandon N. (2020), Recycled materials as a potential replacement to synthetic sound absorbers: a study on denim shoddy and waste jute fibers, *Applied Acoustics*, **159**: 107070, https://doi.org/10.1016/j.apacoust.2019.107070.

35. Rohen L.A. *et al.* (2017), Hemp fiber density using the pycnometry technique, [in:] *Characterization of Minerals, Metals, and Materials*, pp. 423–428, Springer, https://doi.org/10.1007/978-3-319-51382-9_46.

36. Sağlam S., Güzelçimen F., Bingöl D., Özkan U.Y., Ekici B. (2022), An evaluation on acoustic behavior of untreated tree trunks depending on bark physical properties and fiber cell structure, *Journal of Natural Fibers*, **19**(4): 1507–1521, https://doi.org/10.1080/15440478.2020.1779901.

37. Samuel B.T., Barburski M., Witczak E., Puszkarz A.K. (2023), Enhancement of low and medium frequency sound absorption using fabrics and air gaps, *Textile Research Journal*, **93**(21–22): 5112–5123, https://doi.org/10.1177/00405175231186176.

38. Santoni A., Bonfiglio P., Magnani A., Marescotti C., Pompoli F., Fausti P. (2021), A hybrid approach for modelling the acoustic properties of recycled fibre mixtures for automotive applications, *Applied Acoustics*, **182**: 108272, https://doi.org/10.1016/j.apacoust.2021.108272.

39. Selver E. (2019), Acoustic properties of hybrid glass/flax and glass/jute composites consisting of different stacking sequences, *Tekstil ve Mühendis*, **26**(113): 42–51.

40. Sezgin H., Duru S.C., Candan C. (2022), Evaluation of acoustic performance of hemp and cotton fiber reinforced thermoplastic composites, *Uludağ Üniversitesi Mühendislik Fakültesi Dergisi*, **27**(1): 151–162, https://doi.org/10.17482/uumfd.925486.

41. Sezgin H., Kucukali-Ozturk M., Berkalp O.B., Yalcin-Enis I. (2021), Design of composite insulation panels containing 100% recycled cotton fibers and polyethylene/polypropylene packaging wastes, *Journal of Cleaner Production*, **304**: 127132, https://doi.org/10.1016/j.jclepro.2021.127132.

42. Takagi H. (2019), Review of functional properties of natural fiber reinforced polymer composites: thermal insulation, biodegradation and vibration damping properties, *Advanced Composite Materials*, **28**(5): 525–543, https://doi.org/10.1080/09243046.2019.1617093.

43. Textile Exchange (2024), *Materials Market Report*, https://textileexchange.org/knowledge-center/reports/materials-market-report-2024/ (access: 9.02.2026).

44. Unterweger C., Brüggemann O., Fürst C. (2014), Synthetic fibers and thermoplastic short-fiber-reinforced polymers: properties and characterization, *Polymer Composites*, **35**(2): 227–236, https://doi.org/10.1002/pc.22654.

45. Yalcin-Enis I., Kucukali-Ozturk M., Sezgin H. (2019), Risks and management of textile waste, [in:] *Nanoscience and Biotechnology for Environmental Applications*, pp. 29–35, https://doi.org/10.1007/978-3-319-97922-9_2.

46. Yan L., Chouw N., Jayaraman K. (2014), Flax fibre and its composites – a review, *Composites Part B: Engineering*, **56**: 296–317, https://doi.org/10.1016/j.compositesb.2013.08.014.