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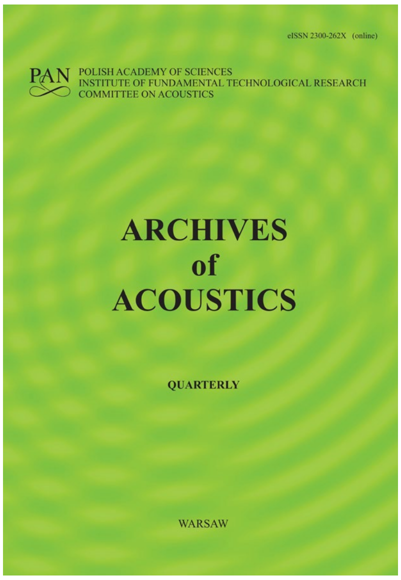

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Development of Sustainable Lightweight Acoustic Composites from Denim, Flax, and Hemp Fibers

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Abstract

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

Keywords

Recycle, denim waste, hemp, flax, linen fabric, cotton, composite, acoustic, sound

Acronyms

NFC – natural fiber composite

SAC – sound absorption coefficient

NRC – noise reduction coefficient

STL – sound transmission loss

PE – polyethylene

PP – polypropylene

PLA – polylactic acid

Hz – Herz

1. Introduction

Environmental concerns and awareness have led to the use of natural fibers in composite materials for achieving 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 have also 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 for the development of 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).

NFC for used in acoustic and other applications can be produced from virgin fibers as well as waste and recycled fibers that further support sustainability. Therefore, promising results obtained in the development of NFC for acoustic applications encouraged the 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, and sugarcane waste, industrial banana fiber waste, industrial waste tea fiber as reinforcing materials in the development of composites for acoustic applications (Ersoy and Kucuk, 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 by throwing away, insitu burning, and composting were used. In some of these studies, hybrid reinforcement materials were used including synthetic fibers such as e-glass in the composites developed (Prabhu et al., 2019; Gokulkumar et al., 2021). As the matrix material, thermoset epoxy resin, polyurethane and polyester binder, and urea formaldehyde/ammonium chloride were used.

On the other hand, the increasing population and therefore the increase in production increased the amount of waste generated in the textile and apparel industry and it becomes 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 area. Textile waste can be classified as production; pre-consumer; and post-consumer waste (Yalcin-Enis et al, 2019). The recycling and reuse of the waste generated in all these stages not only lessen the amount of waste but also lessen the burden on the environment. Because of the need for meeting the global challenges in terms of sustainability and 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 been more crucial (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, but unfortunately, the market share of recycled cotton was estimated at around 1% of total cotton production. On the other hand, the share of recycling is expected to grow significantly in the coming years to achieve a significant reduction in environmental pollution (Textile Exchange, Materials Market Report, 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 that point, 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 PP fibers, ground PP derived from food and cleaning containers, and PE granules obtained from bottle caps serving as matrix materials (Sezgin et al., 2021; Kucukali-Ozturk et al. 2022; Oztemur et al., 2024). 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 PLA binder fibers to develop acoustic insulation panels, while Hassani et al. (2021) created phenolic resin-bonded composites using air-laying 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 study aimed 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/matrix ratios were used in the production of composite panels, their acoustic performances of the composites were 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 composite panels. The cotton fiber was obtained from waste denim fabric; flax fiber was obtained from waste linen fabric. Hemp fiber was supplied in the 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 matrix material in composite panels. Fig. 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/m². The average densities of cotton, flax, hemp, polypropylene, and polyethylene fibers were approximated in accordance with the literature (Lu et al, 2012; Yan et al, 2014; Rohen et al, 2017; Unterweger, 2014; Colakoglu, 2006).


a. b. c. d.

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 were 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 specifications.

Table 1. Characteristics of Materials Used.

Material Type	**Source**	**Fiber Type**	**Form**	**Density (g/cm³)**
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 an effective opening. Fibers were then transferred to the carding machine to obtain fiber webs by feeding a constant weight of fiber. Fiber webs were combined by matrix material with reinforcement/matrix ratios of 80/20% and 60/40% by weight. A series of composite panels were produced by a hydraulic hot press machine. The webs were placed on bottom plate of hot press machine by covering the bottom and top surfaces of the samples with Teflon paper to avoid the sticking of matrix material on the plates. The composite panels were pressed at 170 °C based on the melting temperature of polypropylene/polyethylene matrix material for 1 hour at loads of 10 tons. The samples were then cooled for 1 hour in the press without applying pressure. The production steps of the composite panels are demonstrated in Fig. 2.

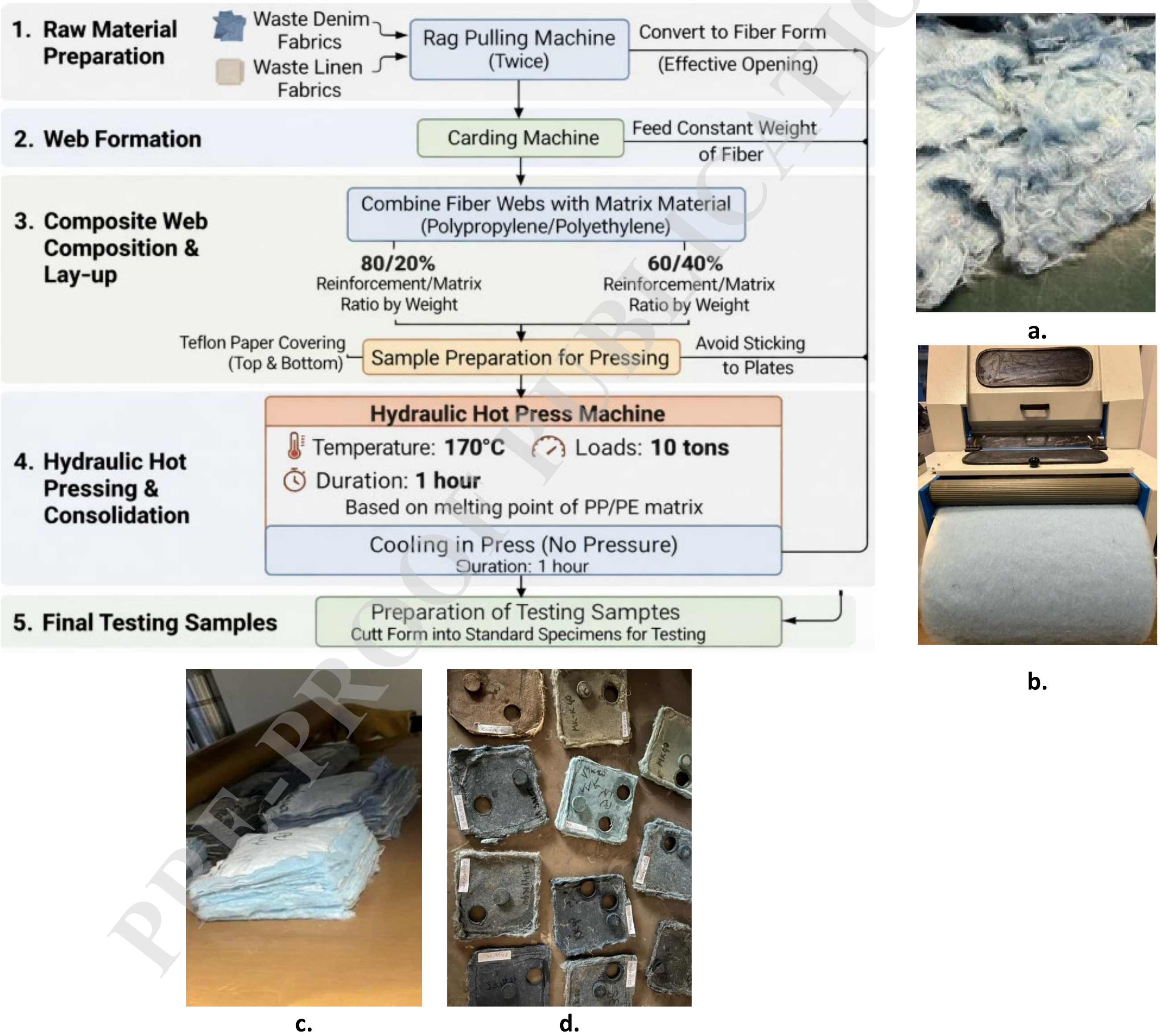

Fig. 2. Production steps of composite panels (a. recycled fibers, b. carding process, c. samples for hot pressing, d. preparation of testing samples).

2.3. *Testing methods*

The thicknesses of the composite panels were measured using a digital caliper. Areal densities were calculated by dividing the measured weight (g) by the measured area of the sample (cm^2). To calculate the bulk density, the areal density was divided by the thickness (cm) of the sample. The porosity of the samples was calculated according to ASTM D2734-16 standard by using Equation (1).

$$\text{Porosity } (\Phi) = \frac{\rho ct - \rho e}{\rho ct} \; x\, 100 \qquad (1)$$

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 between the actual flow path length to the straight distance between the ends of the flow path, was calculated by using the empirical formula in terms of porosity in Equation (2) (Fatima and Mohanty, 2011).

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

The sound absorption coefficient and transmission loss of the samples were measured by an impedance tube (TestSENS acoustic performance measurement system) developed by BIAS Engineering (Turkey) shown in Fig. 3. The impedance tube was preferred because it allows the measurement of small samples. Circular samples with a diameter of 29 mm were prepared, the sound absorption test was conducted according to ASTM E-1050-19 standard using a two-microphone impedance measurement tube, and the sound transmission loss test was conducted according to ASTM E2611-17 standard using a four-microphone impedance measurement tube at frequencies from 200 to 6400 Hz at room temperature. Schematic presentation of impedance tube with double microphones for SAC measurement, and with four microphones for STL measurement are shown in Fig. 4 and 5, respectively.

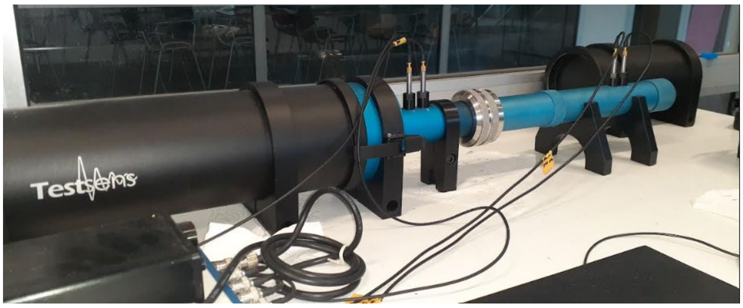

Fig. 3. Impedance tube used for SAC and STL measurements.

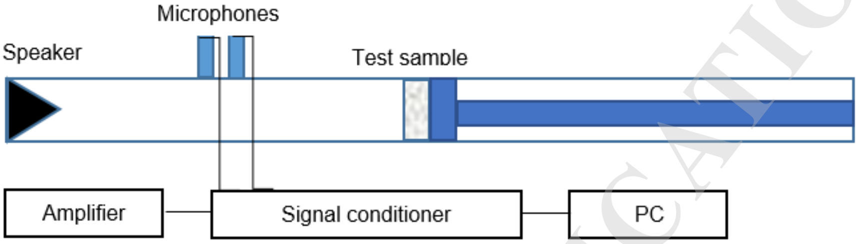

Fig. 4. Schematic presentation of impedance tube with double microphones for SAC measurement.

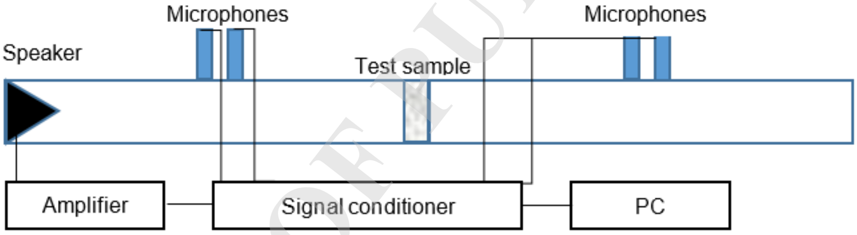

Fig. 5. Schematic presentation of impedance tube with four microphones for STL measurement.

SAC and STL of the samples were calculated by the measurement system according to the Equations (3) and (4):

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

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

NRC, which enables to compare the absorption performance with a single quantitative value, was calculated as the arithmetic mean of the SAC at frequencies 250, 500, 1000, 2000, 3000, and 3500 Hz (Equation 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, SAC values at 3000 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 0.05 according to ASTM C423-17 standard.

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

3. Results and Discussion

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

In the present study, hemp fiber was used as virgin raw fiber in pure hemp and 50/50 blended composites. This means it was not recycled from fabric 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 fibers' elastic recovery ability decreases and they deform less when compressed by the matrix, which increases composite density and reduces porosity. Fibers with high elastic modulus such as hemp (~23.5–90 GPa) 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 (~5.5–12.6 GPa), are more flexible and deformable, often resulting in irregular packing and higher porosity. Although flax fiber has a high stiffness (~27.6–103 GPa) and similar to that of hemp, the flax fiber used in pure flax and 50/50 blend composites was recycled from fabric, and due to the chemical treatments, its stiffness has 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 with 80% and 60% fiber ratio. While lower bulk density and higher porosity were observed in the 80% fiber ratio samples, bulk density increased and porosity decreased with increasing matrix amount in the 60% fiber ratio samples. In addition, tortuosity values increased slightly with increasing matrix ratio and varied between 1.07 and 1.12.

Table 2. Characteristics of 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

Table 3 provides the first peak SAC for each sample, along with the corresponding frequency. It also indicates the frequency range in which SAC exceeded 0.5—commonly considered the threshold for effective sound absorption (Khair et al., 2016). The SAC graphs of the samples were drawn in Fig. 6-8 within the frequency range of 200 and 6400 Hz.

The results highlighted 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, 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 due to the fact that these panels were the thinnest and had the lowest porosity, as mentioned before. Regarding 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.

Table 3. Maximum SAC values of composite panels.

Sample code	Frequency range (Hz) of α > 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

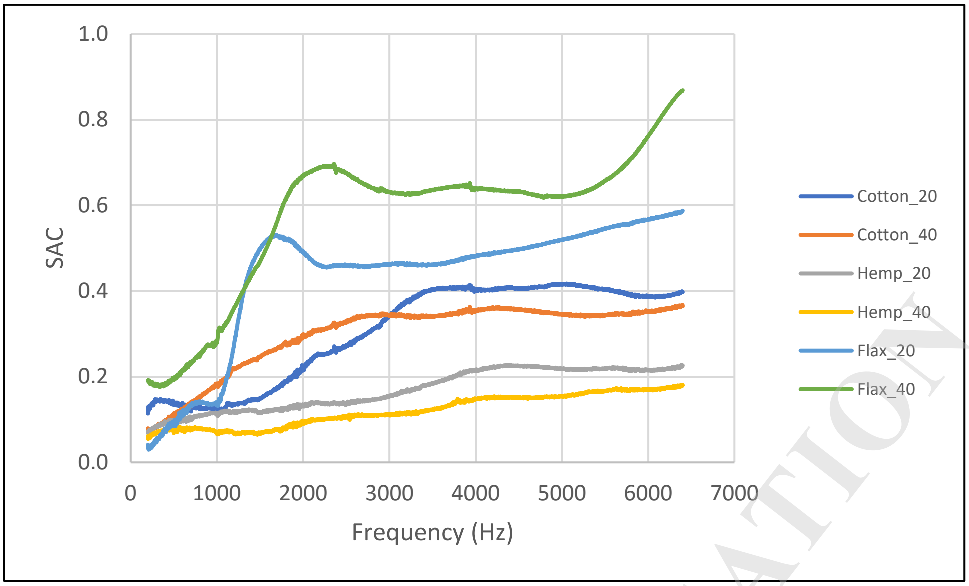

Fig. 6. SAC of pure cotton, flax, and hemp fiber-reinforced composites.

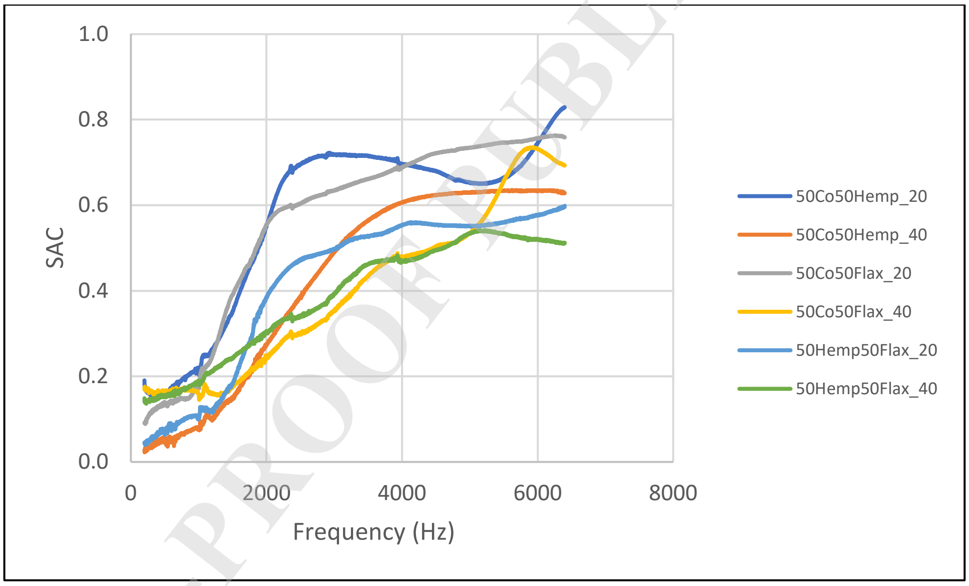

Fig. 7. SAC of 50/50 cotton, flax, and hemp blended fiber-reinforced composites.

In 50/50 blended samples, the combination of cotton with flax or hemp considerably improved sound absorption compared to 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 in the 80/20 blended composites, but peak value was recorded at lower frequencies, especially in samples with higher fiber content. In general, lower SAC values were recorded at higher matrix ratios, which was an expected result due to decreased porosity.

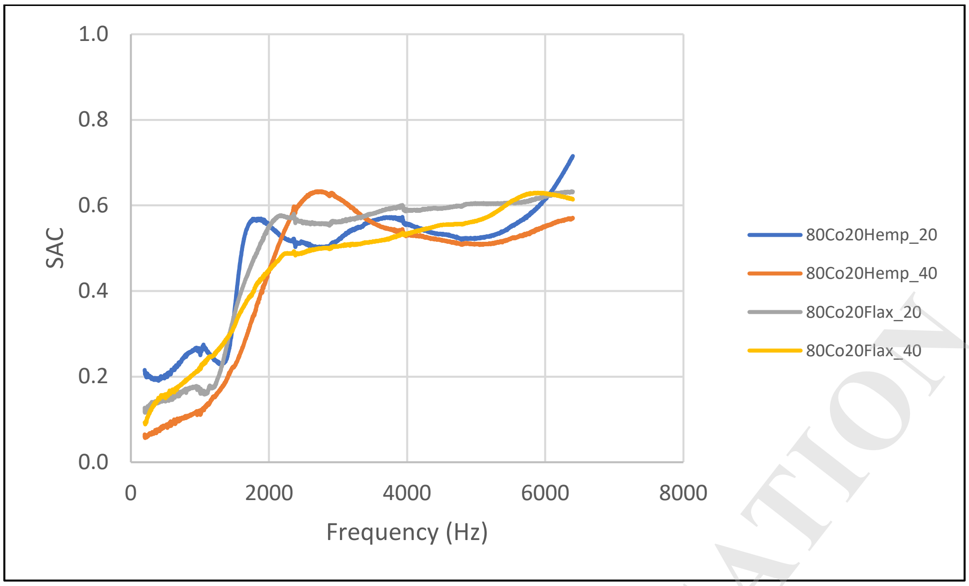

Fig. 8. SAC of 80/20 cotton, flax, and hemp blended fiber-reinforced composites.

Table 4. SACs of composite panels between 250 and 3500 Hz and 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 4 presents the SACs of composite panels between 250 and 3500 Hz and NRC values. 100% flax (Flax_20 and Flax_40) and 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/matrix ratio was also an important factor, and samples containing 60% fiber generally exhibited lower sound absorption coefficients, with performance weakening particularly at mid-frequencies (1000–2000 Hz). An NRC of 0.40 or more indicates effective sound absorption, while values above 0.20 qualify 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. Transmission loss of 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

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

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 mass, an increase in bulk density generally leads to higher STL (Arjunan et al., 2021).

STL results of pure and blended fiber composites revealed a clear dependence on both the fiber type and the matrix ratio. For pure fiber composites (Fig. 9), an increase in matrix content from 20% to 40% generally improved STL values, in agreement with previous findings in the literature (Sezgin et al., 2022). This effect was most pronounced in hemp-based samples, where Hemp_40 consistently exhibited the highest STL across the tested frequency range, followed by cotton and flax. This can be attributed to the higher bulk density of hemp fiber composites contributing to improved transmission loss (Berardi and Iannace, 2015).

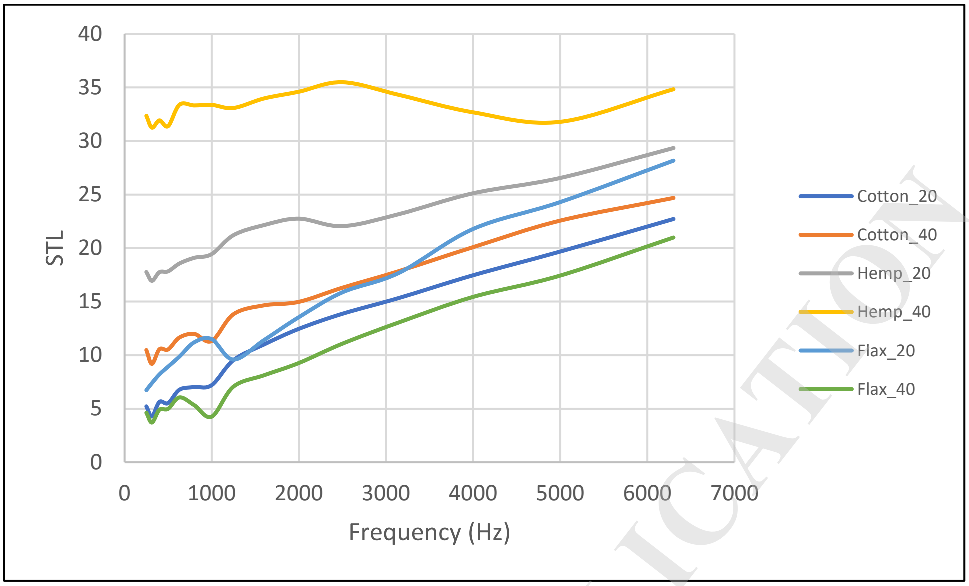

Fig. 9. STL of pure cotton, flax, and hemp fiber reinforced composites.

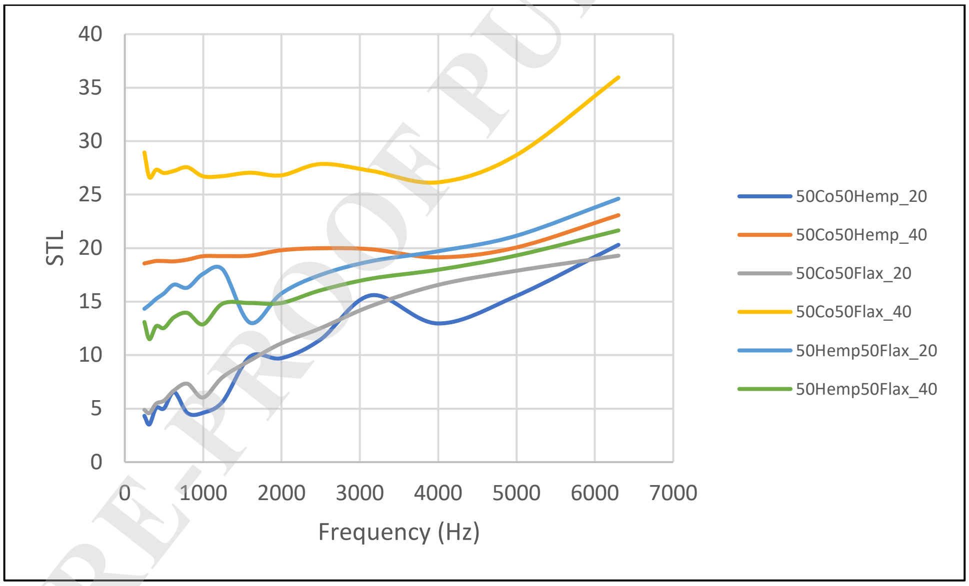

Fig. 10. STL of 50/50 cotton, flax, and hemp blended fiber reinforced composites.

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

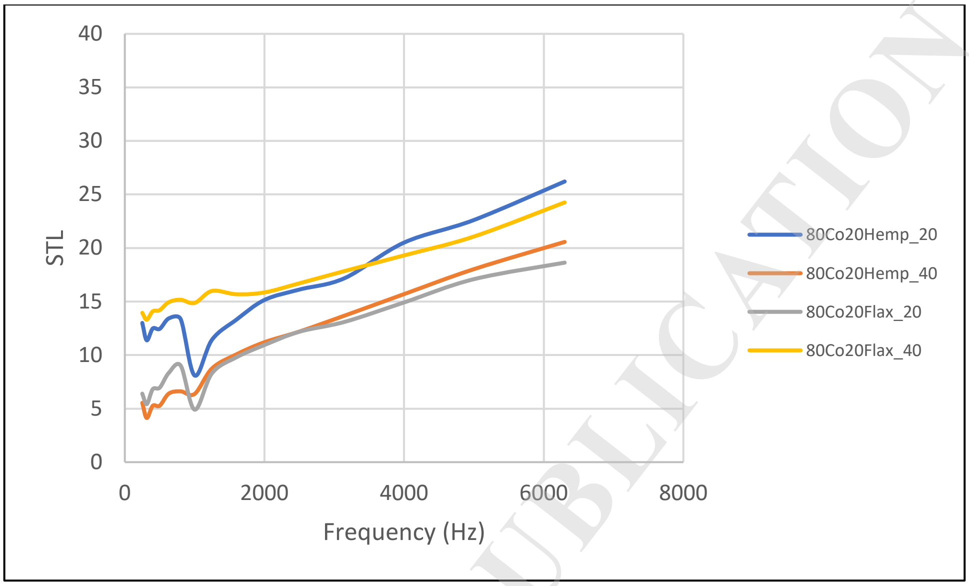

Fig. 11. STL of 80/20 cotton, flax, and hemp blended fiber reinforced composites.

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 acoustic performance.

Specifically, blended composites based on denim waste exhibited higher sound absorption coefficients and NRC values compared to 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 sound transmission loss (STL) due to their higher bulk density and more compact structure.

Increasing the reinforcement content (i.e., reducing matrix ratio) improved sound absorption performance by enhancing porosity and increasing the complexity of 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 like 50% cotton/50% flax or 50% cotton/50% hemp with a low matrix ratio (20%) should be recommended. These configurations achieved high NRC of 0.40, making them effective for broad-spectrum sound absorption. For applications requiring a 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 material 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 in denim production, growing sustainability concerns and evolving consumer expectations have encouraged the incorporation of linen and hemp into denim products. The results of this study indicated 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, while fibers in the present study were distributed in a relatively random manner, future studies should investigate controlled fiber orientation and alignment, as these 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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